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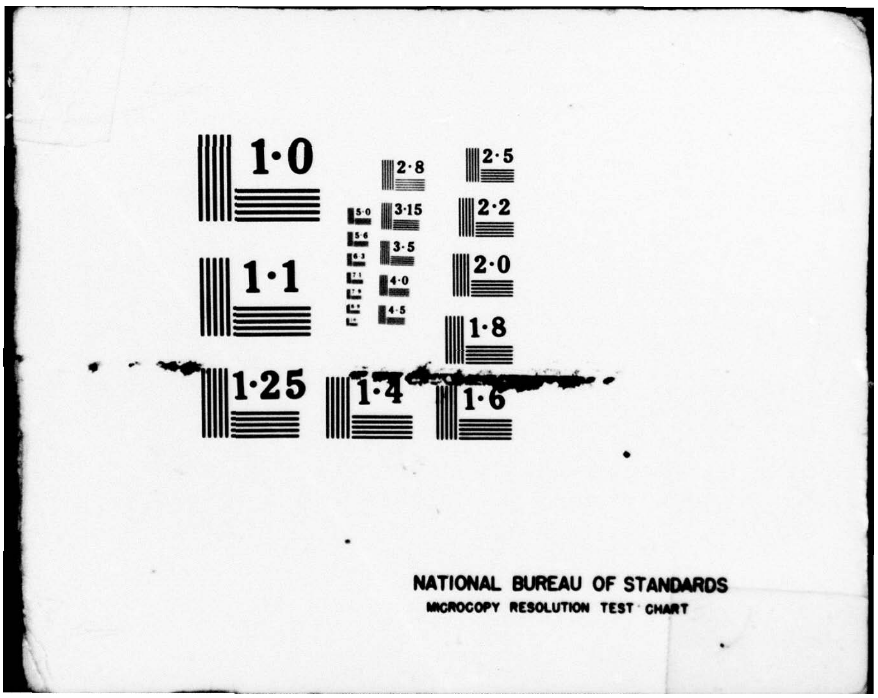
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REPORT NO. CG-D-37-78

LEVEL II

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STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS—PHASE I. A CONTROL THEORY APPROACH

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IMPLEMENTATION TABLE FOR USCG COMMENTS ON DRAFT FINAL SAI REPORT

USCG Comments	Status of Implementation
1. Add U.S. Coast Guard disclaimer page.	1. U.S. Coast Guard disclaimer page added.
2. Use official Department of Transportation cover sheet.	2. Official Department of Transportation cover sheet used.
3. Submit all volumes as one final volume for ease of U.S. Coast Guard publishing and distribution.	3. Final report submitted as one volume.
4. Appendix C added little to the draft report and could be removed from the final report.	4. Appendix C removed from the final report.
5. Change Figure B-19 to B-20.a.	5. Figure B-19 retitled to avoid confusion, page B-41.
6. Add Figure B-21.a on page II-74 as now there are two B-20.a figures.	6. Figure B-21.a added on page II-74.
7. Separate from the report, a physical listing of the preliminary model should be provided with documentation.	7. Physical listing, FORTRAN Decks, and Inputs provided 5/1/78. Documentation necessary for USCG usage will be provided.
8. Relocate properly points N and O in Figure II-5 and on page B-67.	8. Points N and O relocated, page B-71.
9. Cross-track component of motion is to be determined by successive observation of cross-track position (page 10). Comment on successive observations and the time between each.	9. Comments on successive observations added, page 10.
10. It is not clear whether the error maps are a part of the input for a run or are initiated as a first step in a run based on a particular A/N configuration. Please clarify.	10. No change--discussed on page II-29, third paragraph and discussed on page B-37 first paragraph.
11. Discuss how the model incorporates the factors of present rudder angle, drift, velocity vector, and rate of turn when propagating a ship density from a given cell to other cells.	11. Additional discussion of suggested topics, page B-49.
12. Figure 3, Direction of Motion, discuss the obvious cycle or oscillation shown.	12. Discussion of oscillation in direction of motion added, page 14.

USCG Comments	Status of Implementation
13. Discuss why angular velocity is not included as a navigation variable in the straight channel case.	13. Discussion of why angular velocity was not a straight channel navigation variable added, page B-79
14. Discuss the interval used to gather cross-track errors and direction errors and the interval as the along-track cell size for size consideration.	14. Added discussion of suggested topics, page B-49.
15. Comment on the inclusion of ship dimensions in calculating cross-track errors.	15. Added comment on the use of ship dimensions in calculating cross-track errors, page II-27.
16. An acknowledgements page is missing.	16. Added an acknowledgements page.
17. There should be some discussion of the bend model in the Executive Summary.	17. Added discussion of bend model in Executive Summary, page 14.
18. The discussion of safe/grounding domains should include something which indicates that they are dependent on ship angular velocity, wind, current, etc.	18. Additional discussion of suggested topics, page B-69.
19. There is virtually no development of the P-θ maps and/or their use in the main report or the appendices. It would be useful to include it so that the report may "stand alone."	19. Added further development of the P-θ maps and their use, page B-8.
20. Annotated Editorial Comments.	20. Corrected as per request of USCG.

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PREFACE

The recognition of the need for a comprehensive aid to navigation study of this type originated in the U.S. Coast Guard. The Performance of Aids-to-Navigation Systems Study, Phase I, was designed to develop the methodology for the total A/N study. The expedient completion of Phase I was made possible largely through the endeavors of Lt. Commander James Sherrard serving as the Phase I technical monitor.

Thanks must be extended to the Pilots' Association for the Bay and River Delaware, the Sandy Hook Pilots' Association, and the Virginia Pilots' Association for their support of the program throughout the Phase I study.

A debt of gratitude must be extended to Dr. Harouzo Eda of Stevens Institute of Technology who developed the ship maneuvering model that was used to depict ship motion.

The 3rd District Coast Guard Engineering Office was most helpful in supplying necessary technical specifications.

A special thanks must be extended to Captain Richard E. Counselman, President, Virginia Pilots' Association and Captain Joseph Guilday, President, Pilots' Association for the Bay and River Delaware, since largely through their efforts and willingness to help a rapore was developed with the pilots of their respective associations that allowed significant progress in the scientific aspects of aids to navigation. The professionalism and dedication shown by the pilots with whom we had the pleasure of working, made our task much easier.

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16. Abstract
A preliminary methodology for the design and evaluation of systems of aids to navigation in pilot waters is described. The physics of ship maneuvering capability are derived from a hydrodynamic vessel response model. Harbor or waterway segments are characterized by generic scenarios involving a single navigation task. Scenarios are adapted to a real harbor segment by the input of actual dimensions. Any system of aids to navigation may be overlaid. The information derived from the aids to navigation by the mariner is determined through the application of statistical distributions for the psychophysical tasks performed. The psychophysical tasks were identified through theoretical analysis and through formalized interviews with pilots. Data on performance of those tasks were derived from prior work in analogous areas and from a limited amount of experimentation. A model integrates both instantaneous and accumulated estimates of components of position and motion pertinent to the scenario. The model output includes measures of risk/safety. The future effort required to expand and refine the methodology, and to produce an integrated, automated and valid model is described. Appendices describe the human factors analysis and the mathematical development of the model in detail.

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Aids to navigation, Buoys, Electronic aids, LORAN-C, Radar, Ranges, Ship operations, Visual aids, Human factors, Pattern recognition

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METRIC CONVERSION FACTORS

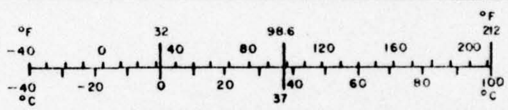
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

INTRODUCTION

This report summarizes the results of SAI's Phase I effort to develop a preliminary methodology for the evaluation of aids to navigation in pilot waters, and identifies the requirements for expanding, refining, and integrating the elements of that methodology into an automated computer-based management tool.

To be responsive to the program objective, the methodology should be applicable to any type of vessel, any waterway, and to any system of aids to navigation, and should result in quantitative measures of risk and traffic facilitation that are sensitive to the effectiveness of the system of aids to navigation.

To achieve the desired degree of response, our approach is based upon the fundamentals of ship maneuvering and both the art and the science of piloting. The resultant methodology, while neither complete nor fully automated, satisfies the program objectives. It provides quantitative measures of risk and traffic facilitation for any vessel that can be characterized by its dimensions and hydrodynamic characteristics, in any waterway described by its geometry and hydrography, and for any aids to navigation which provide information to the mariner.

The methodology developed is sensitive to the influence of the aids to navigation, and to changes in the vessel characteristics and the waterway geometry. Further, it is sensitive to choice criteria. For example, a mariner may elect to follow a desired track with some tolerance, and not take corrective action unless he perceives his vessel to be outside this "region of indifference." The choice criteria permitted with different A/N systems is a potential comparative measure of effectiveness.

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FUNDAMENTAL FACTORS

The methodology was developed from analysis of the interactions of three fundamental factors:

- The vessel
- The waterway
- The mariner.

The first two are physical entities and their static and dynamic relationships can be quantified to a high degree of precision. The latter is much more difficult to characterize objectively and was the focus of the bulk of our investigative effort. Aids to navigation are not included in the fundamental factors. The aids are a variable overlaid on the waterway.

To quantify vessel characteristics we adapted a hydrodynamic ship motion model into a ship maneuver model. The ship maneuver model computes the path swept by the envelope of any vessel whose descriptors include dimensions and hydrodynamic coefficients. In its present state, it accounts for shallow water effects and bank suction, although these effects were not assessed during Phase I. Phase II augmentation will include wind drag and bank cushion effects. This element of the model provides the ability to develop the contours for safe navigation in any waterway geometry, and to characterize and quantify effects which are, or may be, meaningful to the mariner—for example, the rate of change of the relative bearing of a buoy or beacon when the vessel is negotiating a turn.

Charts of all principal U.S. harbors and waterways were examined to identify the smallest set of functional scenarios that encompass all of the tasks performed by the mariner in pilot waters. A scenario includes a segment of a harbor—a channel bend, for example—and a task such as "negotiate the bend at X knots." The segments are defined in generic terms, but when used in the model, actual dimensions of the segment being modeled are applied.

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Aids to navigation are an overlay for the scenario. The user of the model may specify any configuration or combination. The descriptor for each must include position and the characteristics which make them detectable.

The human in the system was much more difficult to characterize. An extensive literature search, the knowledge of staff members and consultants with maritime experience, structured interviews with pilots, and limited experimentation provided the required data. Significant findings are described under the Elements of the Methodology, below.

ORGANIZATION OF THE REPORT

The report is assembled in three units: one (this unit) contains an Executive Summary and a Technical Report; the other two units are Appendices.

The Executive Summary provides an overview of what has been accomplished in Phase I and requirements for Phase II. It presents some examples which illustrate the approach to problems and the application of the methodology.

The Executive Summary is necessarily brief. Its principal contribution is to provide a concise context into which the detailed elements fit which are described in the technical report. Two appendices describe the manner in which basic data were derived and the elements of the model.

HUMAN FACTORS ANALYSIS

Both visual and radio aids to navigation must be assessed with respect to the use the mariner is able to make of them. In restricted waters, navigation texts notwithstanding, the mariner's primary means of data acquistion is direct visual observation, either of objects directly or of their representation on a PPI scope.

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Derivation of psychophysical data for use in the model was an iterative process. Tentative hypotheses were developed from prior experience in analogous situations, assumptions, and simple experiments with perspective drawings. Structured interviews with pilots served to confirm the tentative hypotheses or suggest alternatives. Limited experiments and analysis of interview data led to the postulation of additional hypotheses. These, in turn, were tested with additional pilot interviews narrowly oriented to extract the required information, and by additional experiments. At this point in time, the human factors elements of the Phase I model are consistent with measured psychophysical data for comparable tasks and with data derived from the interviews. However, further work and experimentation are needed to ensure full understanding of the psychophysical processes used by the mariner to extract information from the aids to navigation.

With visual aids, the view is a perspective rather than a plan. Accordingly, much of what follows is described in terms of visual angle (the size of the image as seen by the observer) rather than in actual dimensions. The information inherent in visual aids is related to perspective field.

The scope of the investigation into the psychophysical factors associated with piloting is described in the technical report and substantial detail is contained in Appendix A. The example which follows is illustrative of the type of information developed, and the manner in which it is used.

An <u>observable</u> is that aspect of what is seen or sensed that is actually used. For example, a mariner will use the color, brightness, and period of range lights to identify the range, but when using that range, only the opening of the range beacons is an observable, since this is the information by which he estimates how far off-range he is.

Associated with virtually every observable is a reference point. The reference point is some characteristic of that observable which results in minimum error, e.g., the alignment of two objects, and which serves as a benchmark for quantifying departures from that reference point. The accuracy of information derived from an observable diminishes as the departure from the reference point increases in magnitude.

While observables are psychologically antecedent to reference points, the latter are sometimes identified first and may leave some question as to the observable responsible for the reference point. This occurred in our research into the ability to estimate cross-track location in a straight channel with edges marked by gated buoys. Three reference points were found, one on each edge and one in the center of the channel. That is, the error in the estimate was least at these points (essentially zero at the channel edge, which may be a moot point since the vessel would be aground). It was hypothesized that the observable at or near the channel edge was the horizontal visual angle between buoys; that is, the observer was using the line of buoys as a range. The reference point at mid-channel was attributed to the symmetry seen by the observer—the visual angles formed by the buoys on each side were the same, and the matching of equal visual angles is a simple psychological task. At other points in the channel, the same observables are used, either independently or in concert. However, the identification of angle ratios other than unity, as opposed to matching equal angles, or the estimation of distance off-range from the horizontal visual angle, cannot be performed with precision; hence the error in estimating cross-track position is greater at these other points than at either reference point.

The hypothesis "works," that is, the error distributions are consistent with that reported for equivalent actual navigation situations. Further, it is consistent with the pilot's frequent reference to the "split" of the buoys. However, we are not certain that the correct

observable has been identified. We note that when running near the edge of a channel, the horizontal angle between the buoys is proportional to the distance from the edge, but that the magnitude of this angle changes with distance to the nearest buoy. This would seem to make the task more difficult.

We also note that the slope of the (perspective) line formed by the buoys along a channel edge is equal to the distance to the edge divided by the height of eye. The slope for any given cross-track position (assuming height of eye does not change) is independent of the distance to the nearest buoy or of the buoy spacing. It is possible that slope, rather than the "split," is really the observable. Subsequent experiments suggest that this may also be the observable for the center of channel reference point. The observer may be comparing slopes, rather than visual angles. (The experiment alluded to involved staggered buoys which do not provide visual angle symmetry, yet there was a discernable mid-channel reference point.)

One may ask why it is important to precisely identify the actual observable so long as the magnitude of observer error in estimate of cross-track position can be quantified. Our objective is to be able to evaluate any system of aids to navigation, and one can conceive of two extremes (admittedly far-fetched) to illustrate the need for correct identification of observables. Consider a channel edge marked by a picket fence; only slope would be available as an observable. Then consider a line of lighted beacons, 60 ft high. To an observer with a height of eye approximating 60 ft, only horizontal visual angle would be available. We conclude that it is necessary to correctly identify the observable.

ELEMENTS OF THE METHODOLOGY

In the preceding paragraphs, the fundamental factors—vessel, waterway and mariner—were discussed. The interactions among these factors result in model elements that permit the evaluation of aids to navigation. Following is a brief identification of the elements and a "walk through" of a model run to illustrate the manner in which they are used.

Scenarios

As previously defined, a scenario includes a geometrical description of a waterway and a navigation task (e.g., transit the channel at ten knots, maintaining a distance of 250' ± 50' from the right edge). It also includes an overlay of aids to navigation. The usual procedure has been to hold a scenario constant for a number of evaluations, varying only the aids to navigation. Five types of scenarios were identified for the preliminary methodology: coastal, broad waterway and landfall; harbor or port approach; negotiating a straight channel; negotiating bends and negotiating a constriction. Our Phase I effort has concentrated on straight channel and bend scenarios.

Navigation Variables

Navigation variables are the components of ship motion and position of greatest importance in a scenario. For example, in negotiating a straight channel, cross-track position and the component of direction of motion toward the edge are the navigation variables. These variables represent the information needed by the mariner to safely and expeditiously guide his vessel through the waterway.

Safe and Grounding Domains

For each combination of scenario and vessel type, there are bounds on the areas which can be occupied by the vessel. They may be physical (limiting depth, obstruction, etc.) or regulatory (traffic lane, prohibited area), but for simplicity we use "grounding constraint" to refer to these bounds. For any speed and direction of motion, there is a point beyond which no maneuver permitted by the hydrodynamic characteristics of the vessel can prevent impingement on the grounding constraint. The locus of all such points (for the particular speed and direction of motion) defines a grounding domain.

The vessel characteristics and the geometry for the scenario are used to define the contours of the grounding domains. The complement of any grounding domain is, of course, the safe domain for the

defined speed and direction of motion. Figure 1 illustrates the grounding domain for a straight channel having uniform edges. For clairty, only one speed is included. The contours thus derived define the tolerances available in position and direction of motion to permit safe transit.

Information from the A/N

The navigation variables for the scenario define the information requirements of the mariner. The contribution of each aid, or system of aids, has been assessed for each navigation variable through the human factors investigation. The form of presentation of this information varies, but where it is amenable to "mapping," error maps have been prepared. For example, the mariner's average error in estimating his cross-track position (σ_p) when following a range of specified geometry can be shown on a map with contours or numerical values. The point corresponding to 16,000 feet from the front beacon and 300 feet from the axis would indicate the error at that point. These error maps make possible the comparison of information provided by competing A/N systems.

Measures of Risk and Traffic Facilitation

These measures provide an index of the relative degree of risk and traffic facilitation associated with a system of A/N. They are sensitive to the information content of the A/N, and will also reflect the influence of ship maneuvering characteristics, ambient conditions, and the waterway geometry. A number of parameters indicate relative risk. We have chosen "pilot decision time" for the Phase I model. Pilot decision time is the interval that will elapse before a vessel enters the grounding domain, if no course corrections are made. It indicates the effectiveness of the A/N in providing the navigator with the information required to control his navigation variables. The model can compute the pilot decision times for any point in a scenario. Measures of traffic facilitation are less well developed and their computation has not yet been automated. An availability index is

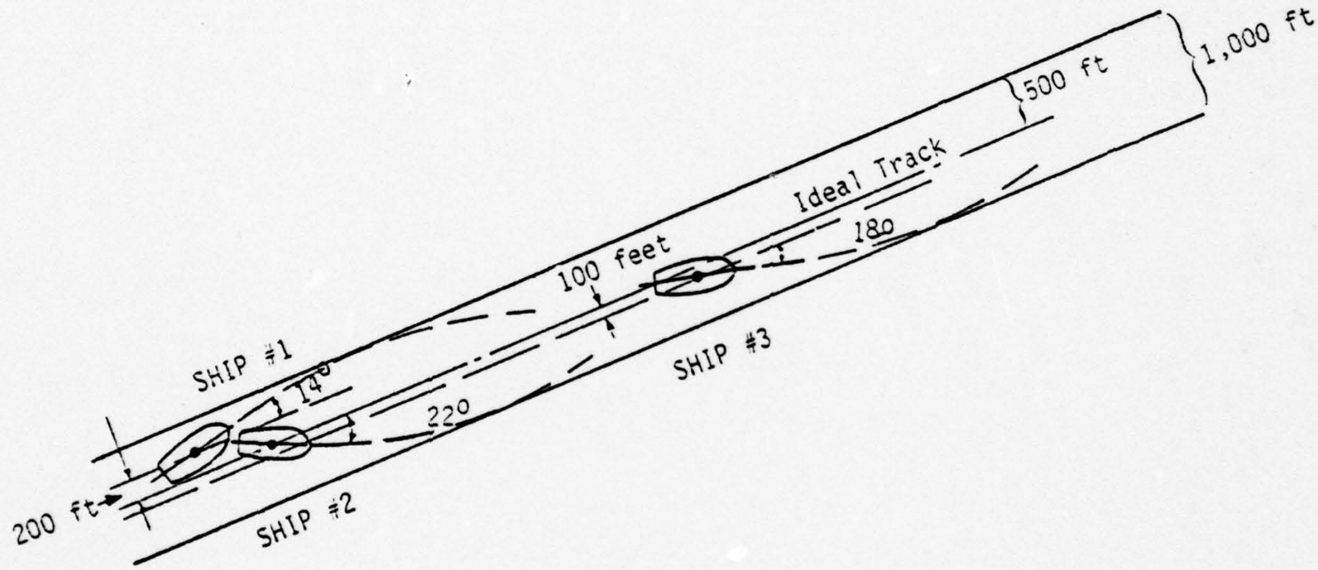

FIGURE 1. GROUNDING DOMAIN FOR A STRAIGHT CHANNEL HAVING UNIFORM EDGES

(17)

proposed as the ratio of the times a segment can be safely used with the information available from the aids to navigation to the times it could be safely used with perfect knowledge of navigation parameters. Application of this index requires the input of distributions of ambient conditions. An additional transit time index, which is the ratio of transit times feasible with the aids to navigation to those attainable with perfect knowledge, is proposed. For this index, objective data on pilots' propensity to increase speed with increased confidence will be needed.

WALK-THROUGH OF A MODEL RUN

A model run measures the effect on the navigation variables of information derived from the aids to navigation in the context of a scenario. The straight channel case, which is the simplest, is a good vehicle for describing the process.

For a straight channel, the navigation variables are cross-track position and the cross-track component of direction of motion. The cross-track position is continuously estimated by the pilot from information he receives from the aids to navigation. Successive estimates of cross-track position provide an estimate of the vessel's direction of motion. Uncertainty in the cross-track position of the vessel converts into uncertainty in the vessel's direction of motion. Cross-track position estimations were implemented at 300 foot intervals during Phase I. As the model observation intervals become smaller the course correction strategy is based upon the maximum information that the particular aid to navigation system can supply a human observer.

The process described above, which we have termed "run and observe," is consistent with the practices of pilots. On entering a channel, the mariner is likely to have a less-than-perfect estimate of the cross-track component of set and drift. He will attempt to gain and hold his desired track, and will alter the course whenever he perceives a departure from that track which exceeds his band of indifference. Successive corrections (assuming that set and drift do not change) will eventually result in a course that provides a direction of motion quite close to that of the channel axis.

For a model run, the vessel type, scenario, navigational aids, and ambient conditions are defined. The navigational aids for a straight channel scenario are in the form of an error map appropriate for the particular set of aids and ambient conditions. A large number of vessels, say 1000, are distributed into cells. Each cell is characterized by an initial cross-track position and direction of motion. "Observations" are made at frequent (selectable) increments, and the distribution of information available from the aids at that increment is applied to each cell. Vessels which perceive out-of-tolerance position will make a correction to their course (proportional to the perceived error) and be redistributed into cells closer to their desired cross-track position and direction of motion.

The content of each cell is tabulated for each interval, thereby producing data on the distribution of navigation variables as a function of distance (or time) along the channel.

Data for seventeen runs with various A/N configurations, assigned tracks, indifference bands, and visibilities are included in Section II.C of the Technical Report. Two typical runs are shown in Figures 2 and 3. Both are for transits of a straight channel in good visibility, and both include an indifference region of ±25'. Figure 2 shows data for buoys on one side only, with the mariner attempting to maintain a track 200' from the buoyed edge. Figure 3 is for a range, with the mariner following the range axis.

The upper graph in each figure shows the cross-track position envelopes, the center graph the direction of motion envelopes for 98 percent (broken lines) and 80 percent (solid lines) of the vessels. The lower graphs show the percentage of vessels with a pilot decision time of 15 minutes or less. These plots represent the distributions of cross-track position and direction of motion as the ships traverse the channel using information from the A/N system. They provide a measure of the utility of the A/N systems to provide mariners with information concerning their ships navigation variables.

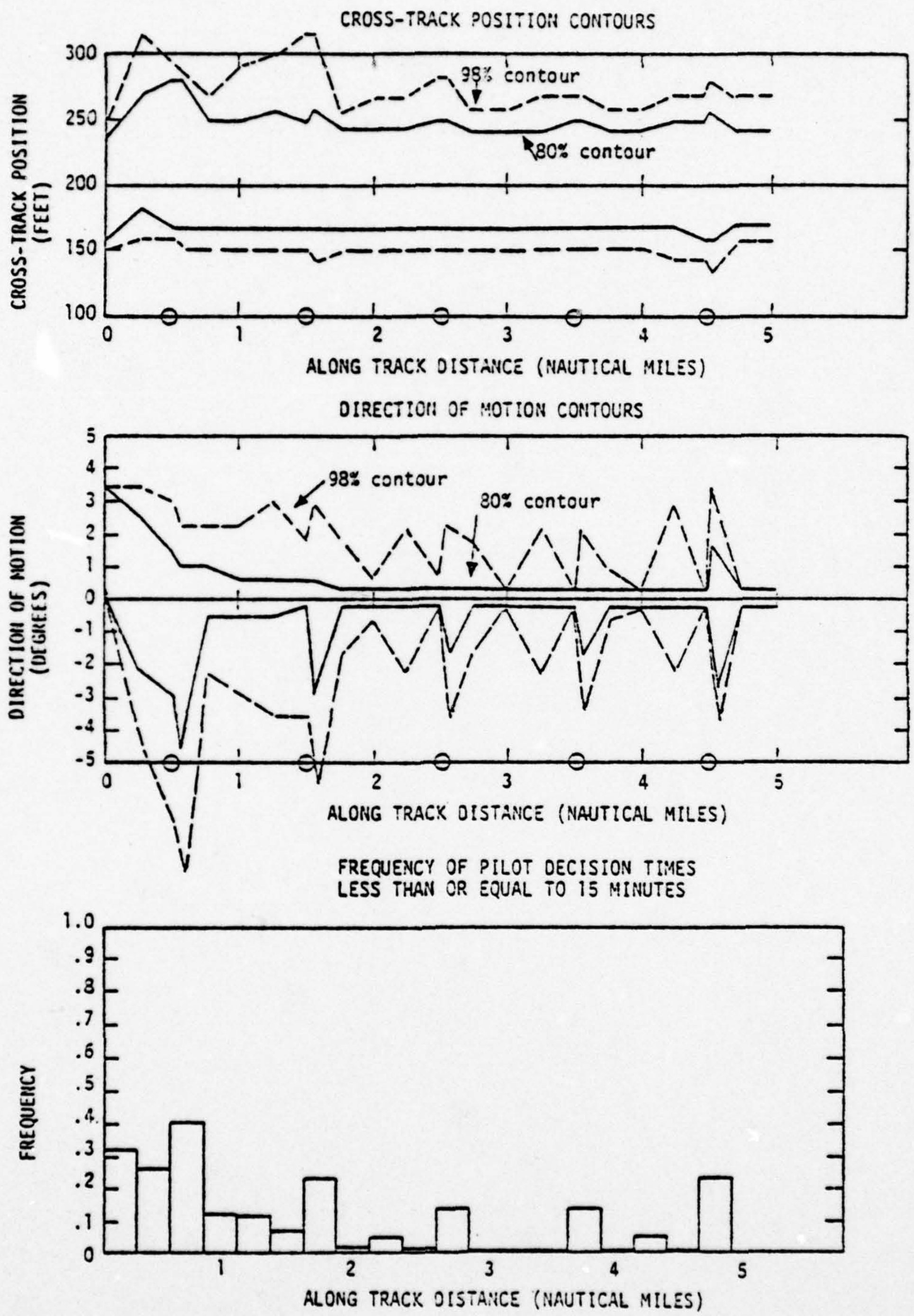

FIGURE 2. BUOYS ONE SIDE/200 FT FROM EDGE

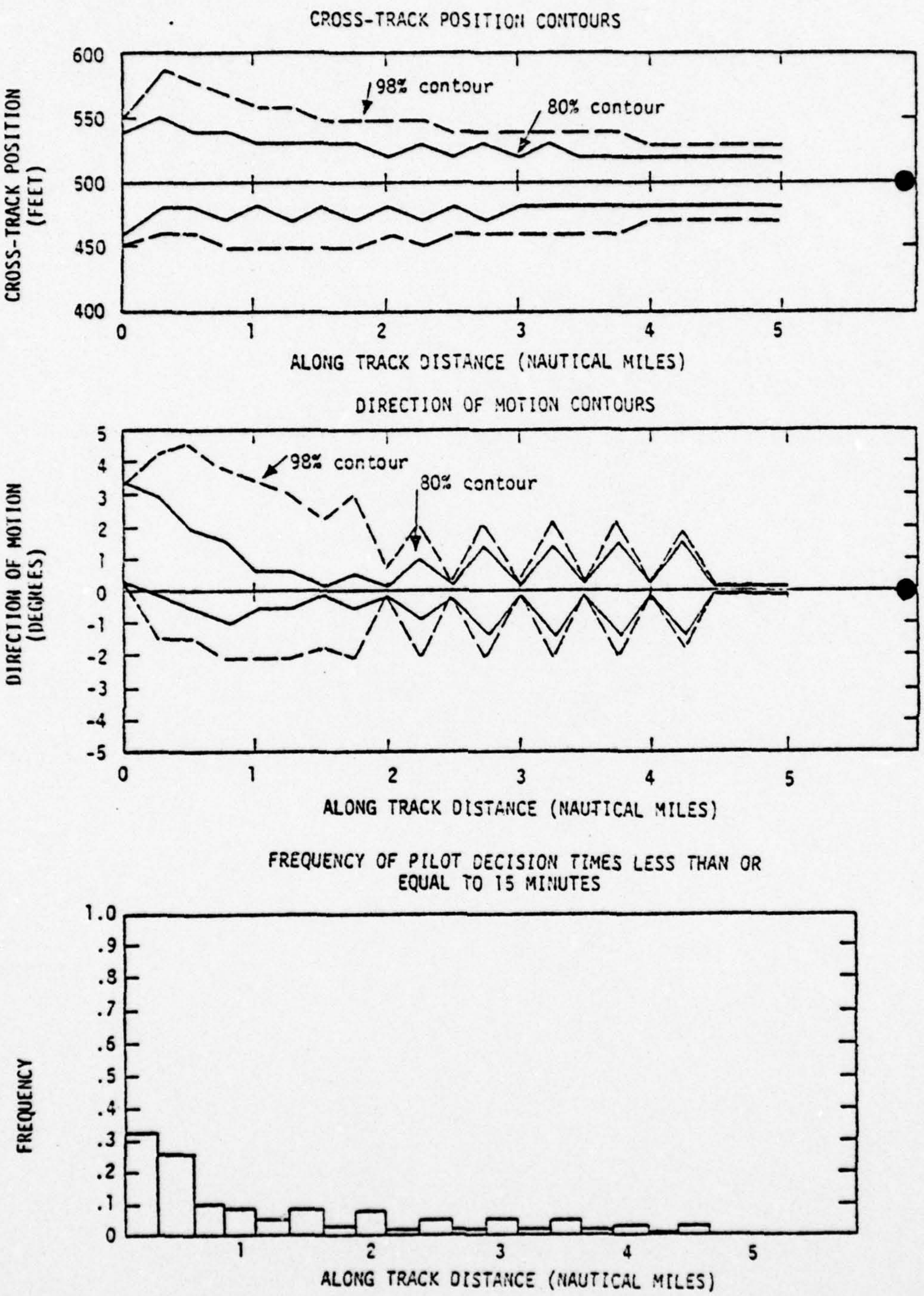

FIGURE 3. RANGE/CENTER OF CHANNEL

It will be noted that most vessels are within $\pm 0.2^{\circ}$ of the desired track after several miles. This is not to imply that this is a practical tolerance for steering a course, but rather that the information provided by the aids to navigation was accurate enough to permit that tolerance.

The symmetrical magnitudes for the direction of motion contours in Figure 3 is due to the desired track being exactly on range. The uncertainty in cross-track position when the desired track is on range is the same to the right as it is to the left.

The oscillatory appearance of the direction of motion contours is due to the course correction process implemented in Phase I. This type of oscillation is not expected in Phase II when a ship maneuver model will be incorporated to characterize ship motion in the control theory model.

Channel Bend Model

A channel bend model was developed during Phase I to characterize the process of navigating the bend scenario using the A/N as control. The Phase I bend model treats the process of navigating a bend in three steps:

- Initiating the bend, where the mariner's action is to apply the initial rudder.
- Monitor the turn, where the mariner's action is to assure that his vessel's track is correct.
- Steady on the new course, where the mariner's action is to assure that his vessel is coming to the new heading correctly.

The first and third of these actions are modeled as distributions of discrete actions. These distributions arise from the imperfect information provided by the A/N as to on-track position on the old leg, which is required to initiate the turn, and cross-track position on the new leg, which is required to steady on the new course. Monitoring the progress of the turn is a "run-and-observe" activity, where control is provided by the A/N.

Input to the Phase I bend model includes distributions for the observables for initiating the turn, monitoring the turn, and aligning on the new leg. Real ship motion is incorporated using the ship maneuver model. Outputs include the distribution of ship positions in navigating the bend, arising from the control provided by the A/N. An example bend analysis is presented in the main body of the report.

REQUIREMENTS FOR PHASE II

The limited time available for Phase I dictated a basic, skeletonized approach for the model. Emphasis was on creating an inherent capability to do most of the things that might be required, but actually doing only those needed to prove that the methodology was sound. An additional constraint was imposed by the sparseness of basic knowledge of the cognitive processes involved in navigation and piloting, and the need to devote substantial effort to ensure realistic treatment of this most important area.

The effort to date leads to the conclusion that the development of a model for the evaluation of aids to navigation, with sufficient accuracy and sensitivity to be a valuable management tool, is both feasible and practical. The requirements for the second phase fall into five groups:

- Model additional scenarios and refine those already developed
- Integration and automation of the modules
- Acquisition of basic data.
- Model validation
- Special topics.

These requirements are discussed briefly in the following paragraphs.

Needed refinements and modifications include:

- Expand file of hydrodynamic coefficients to include all vessel types common to U.S. waters. Acquire data for computation of maneuvering characteristics of common combinations of tugs and barges. Modify the ship operations model to account for all bank effects and wind drag effects.

- Automate the routines for generating safe and grounding domains.

- Refine the error function distributions to reflect skew in those distributions. (Skew is accounted for in the preliminary models by the manner in which the functions are used, but not in the functions themselves.)

- Refine the run and observe model to more realistically reflect pilot actions. Derive maneuvers for correcting cross-track position which are consistent with the vessel's actual maneuvering characteristics and with the distribution of pilot strategies.

- Extend the capability of the bend model to include a distribution of combinations of starting points and turning rates. Refine the monitoring function to integrate information received from multiple observables. Add the capability for sinuous channels.

- Assess the need for error functions for observables unique to the constriction scenario, and develop those required. (See comments on real-time motion detection.)

- Modify the channel alignment module to include optional additional aids to navigation, effects of current shear, and other unique features that may apply to the scenario.

- Determine thresholds for real-time detection of components of motion and develop routines for application of this information category

- Identify the sources, other than A/N, which provide information on navigation variables. Categorize for either general or special case (unique situation) application. Add these effects to the model.

Model Integration

The objective is to integrate all of the modules into a single computer program that would permit user specification and input of all variables, and would result in the output of the measures of risk and traffic facilitation as well as other related or intermediate results.

The manner in which the model is integrated will depend, in part, on the skill and capabilities of the data processing staff available to the using organization, and on any constraints which may be placed on the variables permitted. If, for example, the model is to be used by field activities having only limited staff, it may be necessary to incorporate a query-response module to ensure input of all variables. The specification for the integrated model will be developed in close coordination with Coast Guard officials.

Acquisition of Basic Data

The paucity of psychophysical data relating to navigation and piloting requires the design and conduct of experiments to ensure that

the appropriate observables have been identified, and that the error functions associated with them are adequately quantified. In addition to laboratory experiments, structured interviews are needed to ensure that all available observables used in monitoring turns and negotiating constrictions have been identified.

Information on the ability of individuals to interpret radar presentations and to derive from them information on navigation variables through direct visual observation of the display is required to accurately evaluate the contributions of various types of A/N to radar piloting.

A mariner estimating position from the observation of A/N will not be perfectly accurate. If he notes a difference in successive observations, he may take corrective action or he may, recognizing his probability of error, defer action pending another "look" to confirm or deny the trend. The mechanism by which mariners react to or compensate for perceptual variability needs to be more fully understood to enhance the accuracy and realism of the run and observe model. Of possibly greater importance, the mechanism may place a limit on the utility of improved accuracy from A/N. If, indeed, the mariner has a region of indifference, safety may depend on the width of that region as well as on the aids. If the region of indifference increases with better aids, a measure of safety may be insensitive to improvements in the aids because the increased region offsets their benefits. It appears necessary to decide whether to model the aids with respect to their potential when the users are being as precise as possible, or with respect to probable actual use.

Model Validation

A model purports to simulate a real process so that the behavior of that process can be predicted over a range of conditions impractical or impossible to produce in full scale. If the elements of the process have been characterized in sufficient detail, and the mathematical

expressions define those elements and their interactions adequately, the model is likely to provide an adequate prediction of behavior. There is always risk that an element has been omitted, an interaction not identified, or a series of approximations made that combine to produce an anomalous output.

The model should be validated, both in its parts and as an entirety. The output of the ship maneuver model can be validated by comparison with a hydrodynamic model that has already been validated. The human factors modules can be validated by laboratory experiments and, finally, the output of the entire model can be compared with performance on a simulator. However, highest confidence in the model will require comparison of its predictions with actual navigation of a waterway or of selected segments of waterways.

Special Topics for Investigation

The major categories above do not encompass several isolated special topics that should be investigated in Phase II. These are:

- Detection and Identification of A/N. The detectability of aids to navigation by visual or radar means is readily quantifiable. The parameters which govern detectability should be incorporated into the model to ensure that the information derived from the A/N is realistically related to that which would be available for the ambient conditions. The problem of identification is more subtle. When the mariner has visual orientation, he can readily identify the aids of importance to him. However, when he is attempting to gain visual orientation (e.g., when making a transition from plotted positions to direct visual observation in preparing to enter a harbor), the time required for positive identification and the probability of incorrect identification of key A/N should be considered. In particular, it is necessary to quantify the ability to identify a

specific aid when it is in proximity with other aids of roughly similar characteristics

- _Traffic Facilitation_. A method for measuring the contribution of A/N to traffic facilitation must be incorporated into the model. The measure proposed is the ratio of the time that a segment is available for safe transit with a given system of navigation aids to that which would be available with perfect knowledge of navigation variables. A second measure which may also be applicable is the ratio of transit times (given system of navigation aids to perfect knowledge of navigation variables). The difficulty in applying any measure of traffic facilitation is the need for data on ambient conditions (particularly visibility and wind) and their correlation.
- _Buoy Stationing Error_. The effect of the displacement of buoys from their charted positions must be reflected in the functions which quantify errors in the information available from the A/N. The errors due to survey (anchor positioning) and scope must be included in all cases where buoys are used. Provision must be made to allow for additional error due to dragging. The model must be realistic in applying the effects of stationing error; at some point the magnitude makes the error obvious, and the mariner will ignore the buoy, resulting in a missing, rather than a misleading aid.

CONCLUSIONS

The most significant conclusion drawn from the Phase I effort is that a model for evaluating aids to navigation, having sufficient sensitivity and accuracy to become a valuable management tool, is both feasible and practical.

The modeling of the interaction of the mariner with the aids to navigation (and the harbor geometry) can be quantified with substantial accuracy, and can be applied to various types and configurations of A/N. In particular:

- The "run and observe" process appears to be a basic technique for navigation in confined waterways.
- The number of observables used for deriving information from A/N appears to be quite limited:
  - a. matching visual angles (or slopes);
  - b. matching visual angle (or slope) to a remembered reference;
  - c. ranging (related to b, above);
  - d. direct distance estimation, and
  - e. bearing and rate of bearing change for a fixed object.
- The concept of a reference point is the foundation for quantifying the errors in observables. It is consistent with all data derived from human factors literature, pilot interviews, and experimentation.

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BASIC ANALYTIC TECHNIQUE FOR DESIGN & EVALUATION
OF SYSTEMS OF AIDS TO NAVIGATION

I. INTRODUCTION

The technical report is divided into two major areas. Part II covers the results of the Phase I effort and Part III describes the future work required to translate the preliminary methodology into a complete, integrated and automated model. Part II is in narrative form with emphasis on what was learned in the Phase I effort and examples of the application of the methodology in typical situations.

Detailed descriptions of how data were acquired, identification of sources, the derivation of equations, descriptions of the model elements, and the results of model runs are contained in Appendix A (Human Factors Analysis) and Appendix B (Mathematical Modeling and Methodology).

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II. PHASE I ACCOMPLISHMENTS

II.A Elements of the Methodology

The elements that comprise our approach to the problem of developing a model by which requirements for A/N can be assessed are presented in this section.

II.A.1 Risk and Traffic Facilitation Measures

Required are measures of risk and traffic facilitation that are sensitive to the important elements of the problem. Above all, the measures should be sensitive to the information content inherent in systems of A/N. The measures should also show the influence of ship maneuver characteristics; environmental characteristics such as wind, current, and visibility; and waterway characteristics such as channel width and depth, shape of channel banks, shape and severity of channel bends. Finally, the measures should be sensitive to choice criteria where this is appropriate. An example of the type of navigation choice criteria which the measures should be sensitive to is the mariner's indifference region in navigating a straight channel. That is, the mariner may only wish to be close to a desired track and may not take corrective action unless he perceives himself to be greater than, say, 50 ft. from the desired track. In fact, the choice criteria permitted with different A/N systems could be used as a comparative measure of effectiveness of those A/N systems.

We have developed a methodology that is sensitive to the influence of each of the above. In fact, the influence of any of the above elements of the problem can be assessed through sensitivity analyses, since each element is well defined in the model. The influence of each element of the problem is separable, allowing assessment of combinations of the elements.

II.A.2 Navigation Scenarios

A methodology is required that will treat all of the navigational tasks mariners are required to perform on restricted waterways. We have defined five navigation scenarios of interest for the Phase I program:

- Coastal, Broad Waterway and Landfall; characterized by navigation in open water where major visual and radio A/N are used (lighthouses, radar, LORAN).
- Harbor or Port Area Approach; characterized by transition from an open waterway to a restricted waterway. The channel alignment problem is an important aspect of this scenario.
- Negotiating A Straight Channel; characterized by a straight channel of restricted width, marked with A/N intended to allow relatively precise fixing of cross-track position.
- Negotiating Turns; characterized by channel bends, or the intersection of two successive straight channel legs. The function of A/N is to permit the turn to be executed without grounding. This scenario also includes sinuous channels.
- Negotiating A Constriction; characterized by a vessel passing through a narrow opening, such as a drawbridge.

Dividing the navigation problem into scenarios allows the analysis to be concentrated on the information required by the navigator to complete the task represented by each scenario, and on the information provided by systems of A/N to complete that task.

We have treated straight channels and bends in some depth in Phase I. In so doing, we believe we have many of the insights required to treat the channel alignment problem, which is an important aspect of the Harbor or Port Area Approach scenario. EASAMS Ltd. has treated the coastal navigation scenario. We have reviewed this analysis and

conclude that it is adequate; we did not independently analyze this scenario during Phase I. We have not explicitly treated the constriction problem (except to identify the basic navigational tasks involved), but don't believe that it will significantly differ from the straight channel scenario with more stringent navigation requirements, with perhaps some elements of the channel alignment task.

II.A.3 Safe/Grounding Domains

In order to measure risk for the navigation scenarios, it is necessary to examine the allowable limits of ship operation for each scenario. These allowable limits are referred to as the safe domain. For a particular ship, they are precisely defined in terms of components of the ship position and motion. The complement of the safe domain is the set of components of ship motion and position that will assure that the ship will ground or ram, no matter what actions are taken by the mariner. These components are defined as the grounding domain. In general, different components of ship position and motion could be important for different navigation scenarios.

Obviously, precise definitions of safe and grounding domains depend on ship characteristics; harbor characteristics such as channel width, bank shape and water depth; and environmental characteristics such as wind and current. Some of these influences will be more important than others in characterizing the domains for a navigation scenario; a subset of the influences will adequately characterize a given scenario. A particular harbor complex could be viewed as being characterized by the safe/grounding domains for a typical ship type using that harbor; or perhaps for a ship type that represents the most stringent requirements for the waterway.

The safe/grounding domains represent constraints on ship positions and movements, and are one of two aspects of the risk methodology. The other aspect of the methodology is the set of positions and movements that could be expected if mariners were using a particular

A/N system in the confined waterway. This is discussed in future sections.

II.A.4 Navigation Variables

The navigation variables are defined as the components of ship position and motion that are most important for a particular navigation scenario. They are important because the channel complex and the navigation requirements of the scenario impose constraints on these particular components. As an example, consider the requirements for navigating a straight channel. To avoid grounding, it is critical that the ship's cross-track position be a safe distance from the channel edge, and the ship's direction of motion be nearly parallel to the channel axis. The component of motion toward a channel edge is the critical component for grounding on the channel edge. On-track position and the on-track component of motion are not critical to avoid grounding. The critical components of ship's position and motion for the straight channel scenario are cross-track position and direction of motion with respect to the channel edge. These are the navigation variables for the straight channel navigation scenario.

Therefore, for the straight channel scenario, the mariner must have information concerning his cross-track position and direction of motion to avoid going aground. This is the critical information for the A/N to provide for this scenario. Also, the safe and grounding domains for a navigation scenario are defined in terms of the navigation variables.

II.A.5 Information from the A/N

The useful information from a system of A/N is that concerning the navigation variables for the navigation scenario at hand. For instance, the critical information required for navigating a straight channel is cross-track position and direction of ship motion. Current Aids to Navigation supply this information in various ways. For example, visual A/N systems like ranges present visual patterns to the mariner

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from which cross-track position can be derived. A range presents alignment information in terms of the horizontal component of the visual angle formed by the open range by which a mariner can estimate his cross-track position as a deviation from the on-range position. The ability of the mariner to fix cross-track position generally degrades as the mariner moves off-range, since it becomes an increasingly more difficult psychological task to match the observed visual angle presented by the front and rear ranges to position off-range. (This phenomenon is discussed in greater detail in Section II.B.2 and Appendix A as an application of the reference point notion of psychological literature.) The range provides little direct information concerning ship's direction of motion, except when the cross-track component of direction of motion can be fixed by comparing cross-track positions on successive observations. (We have termed this process of setting direction of motion "implicit run and observe"; it is discussed in detail in Section II.B.3.)

Some radio A/N systems display cross-track position information directly on a screen, e.g., a radar with a PPI screen. The process by which the mariner extracts information concerning his ship's direction of motion is still run and observe, however, since this navigation variable is estimated by successive radar fixes.

The ability of the mariner to fix the navigation variables (or to estimate that they are adequate for safe navigation) is a critical element of our risk methodology. Comparing this ability with the constraints on the navigation variables provided by grounding domains is the essence of our approach to risk analysis.

II.B Implementation of the Methodology

This section discusses the specific approaches we have taken to model and quantify each of the elements of the methodology discussed in the previous section.

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II.B.1 Systems of Aids to Navigation

The Phase I effort concentrated primarily on visual A/N. However, because of the somewhat general applicability of the run and observe navigation process, two preliminary radio aids examples were completed, namely, a radar taking fixes on buoys lining a channel (PPI scope display), and a LORAN C case.

Basically, visual A/N systems which mark straight channel segments, and A/N placed to aid turning from one channel segment on to another, or to aid in maneuvering a defined waterway, were the only visual A/N considered in Phase I. Visual A/N to assist in the navigation tasks of channel alignment, bends, and navigating a straight channel were included.

Development of the Phase I methodology was oriented toward analyzing the ability of current A/N systems to provide the type of information most critical to the navigation process, i.e., information concerning the navigation variables.

Table II-1 lists the example A/N systems and navigation scenarios for which preliminary analyses were performed during this phase.

II.B.2 Information from A/N Systems

In measuring information provided by a system of A/N, it is necessary to keep in mind that the information is being extracted by a human observer. Usable information may be considerably less than what a geometric analysis would show to be available. The aids must be considered as the user sees them, and they must be assessed with respect to the use he is actually able to make of them. In particular, visual aids must be assessed with respect to the information available in a perspective view, not in a plan view. For that reason, much of what follows will describe aids in terms of visual angle rather than in terms of actual dimensions. Visual angle is a measure of the size of the image cast on the eye's light-sensitive retina, so it describes the dimensions of the perspective view rather than of the aids themselves.

TABLE II-1. DEFINITION OF CASES

CASE	AIDS TO NAVIGATION	MARINER'S DESIRED TRACK	COMMENTS
1. Gated buoys	Gated buoys, 1 n. mi. separation	Center of Channel	
2. Gated buoys	Same as above	Center of Channel	Indifference zone = 1 ft.
3. Gated buoys	Same as above	300 feet from left edge	
4. Buoys one side	Buoys one side 1 n. mi. separation	Center of Channel	
5. Buoys one side	Same as above	200 feet from edge marked with buoys	
6. Range	Range only	On-Range	All range cases run with 1 n. mi. between range marks.
7. Range	Range only	On-Range	Indifference zone = 1 foot.
8. Range	Range only	200 ft. off-range	
9. Range	Range plus buoys one side	On-Range	Buoys used by mariner only to establish on-track position.
10. Range	Same as above	200 ft. off-range	Same as above.
11. Buoys one side	Buoys one side 1 n. mi. separation.	100 ft. from edge marked with buoys.	
12. Buoys one side	Same as above	Same as above	Indifference zone = 1 foot.
13. Buoys one side	Same as above	Same as above	Poor visibility case: Information provided only when buoy is abeam.
14. Buoys one side	Same as above	Same as above	Poor visibility case. Indifference zone = 1 foot.
15. Radar PPI scope	Radar fixing on buoys on one side	Center of Channel	Radar uses information only from buoys on channel edge.
16. Loran - C	Loran - C	Center of Channel	σ reflects only short-term variable errors.
17. Gated buoys	1 n. mi. separation	Center of Channel	250,000 DWT Vessel

Initial Conditions: P distribution between $\pm$ 50 ft. of ideal track. ψ distributed between .2 and 3.4 degrees. Indifference zones are 25 ft. except where indicated. Vessels used are 80,000 DWT except where indicated.

Since extraction of information from A/N is an active process, analysis of that information is an analysis of tasks performed by the human observer. The discussion that follows is organized in terms of those tasks. A similar but more detailed discussion appears in Appendix A .

II.B.2.1 Estimating Cross-Track Location in A Straight Channel. Two concepts have been particularly valuable in our analysis of the ability to judge position with respect to the two sides of a channel. One is that of an observable, that aspect of what is seen that is actually used. A mariner using a range, for example, may note only how far the range is open, and may make no use of the brightness and color of the lights, the vertical separation of the lights, etc. How far the range is open is serving as an observable for determining how far off range the mariner is. Other aspects may help him identify the range, but unless they provide him with information about his ship's position, they are not observables.

Associated with an observable is usually a reference point. A reference point is a location from which the observable may be used with a minimum of error. In the example above, it is possible for a mariner to identify himself as being on-range (range closed) with considerable precision. He will be less accurate in judging himself to be a certain distance off-range (range open by a specified amount, for any known distance from a known range). The on-range position is therefore the reference point associated with the observable of openness. The salience of the reference point is suggested by the description above: the mariner keeping the range open by a specified amount is trying to establish a certain distance off-range; that is, a certain distance from the reference point "on-range."

Observables are psychologically antecedent to reference points. However, the latter are often identified first, as when experimentation shows a location in a channel that can be identified especially accurately.

There may be some question about what the observable is which is responsible for a reference point, or there may be more than one observable having a given reference point. For estimating cross-track location in a straight channel, three reference points have been identified, and it will be convenient to organize discussion around them.

Edge of Channel. The edge of the channel serves as a reference point, provided that the edge is marked with buoys. Informal experiments using ourselves as subjects provide extremely low error for simulated positions on the channel edge. The reason appears to be that, from the edge, the buoys are aligned along the line of sight; that is, they are on-range. Ranging is widely recognized as a relatively easy task, and pilots commonly supplement official range lights with ranges of opportunity (e.g., the crotch of a tree aligned with the edge of a building).

The observable associated with the edge of channel reference point is some aspect of the openness of the ranged objects. Pilots regularly use ranges for the purpose of maintaining off-range positions, and they frequently mention "the split of the buoys" when discussing navigation along a channel edge. The problem is to determine exactly what part of what is seen is used to decide how far the range is open. There are two fairly obvious candidates. One is the horizontal component of the visual angle separating the buoys; for any fixed distance from the nearest buoy, that component varies directly with distance from the channel edge, and it is independent of buoy spacing and height of eye. The other is the slope of the line connecting the buoys, defined here as the ratio of the horizontal to the vertical component of the visual angle separating the buoys. (We have used the reciprocal of the usual geometric definition of slope in order to avoid having low error associated with infinite slope at the reference point.) Slope has the advantage that, for any given height of eye, it remains constant for any given distance from the channel edge, regardless of distance to the nearest buoy.

The plausibility of an interpretation in terms of slope was supported by an experiment performed to measure the error in judging openness of a range (see Appendix A). Expressed as changes in slope, error increased linearly with slope. Expressed as changes in horizontal separation, error was a function of both horizontal and vertical separation of the range marks. Interpretation in terms of slope is further supported by evidence that observers can match slopes of port and starboard lines of buoys in order to identify the center of a channel; this evidence comes from an informal experiment performed on our channel perspective simulator (see Appendix A).

Center of Channel. The center of the channel serves as a reference point if both edges of the channel are marked with buoys, or if the center is marked with a range.

Consideration of the observable associated with a range is the same as that for the edge of channel reference point with one exception. Since the range lights are not in a plane parallel with the surface of the water, the slope of the line connecting the lights is not constant for a given distance off-range. Thus, if slope is the observable for ranges, it is still necessary for the pilot to know his distance from the range, and to be familiar with the range itself, in order to know what slope is associated with what distance from the reference point. The only exception is on the reference point itself, for there the slope is zero regardless of the range's distance and construction.

Of course, there is nothing about a range which makes the center of the channel the reference point, other than the custom of using ranges to mark centers. The reference point is the on-range position, wherever that may be.

If the channel is marked with buoys along both edges, the center appears to be a reference point regardless of the spacing of the buoys. If the buoys are gated, there is an obvious symmetry in the visual pattern. From the center of the channel, the visual angle separating

any two port buoys is the same as the visual angle separating the corresponding starboard buoys. Since judgment of equality is a particularly easy task, we have regarded comparison of the visual angles as the psychological operation yielding position information from near the center of a channel marked with gated buoys. We have modeled the comparison by taking the ratio of angles on opposite sides as the observable. Our choice of the ratio has been supported by our psychophysics consultant, John Baird; and he has provided us with the necessary information for a quantitative estimate of error for this observable.

The importance of the symmetrical pattern provided by gated buoys was supported by data collected in interviews with members of the Sandy Hook Pilots Association. Symmetry was a sufficient cue for judging the center of the channel, even in diagrams which destroyed most of the perspective cues. An informal experiment on our channel perspective simulator (see Appendix A) indicates that equal visual angles on port and starboard may not be a necessary condition for there being a reference point at the center. Error was lower at the center than somewhat to the side of it for a simulated channel marked with staggered buoys. Apparently the symmetry of the slopes of the two lines is sufficient to create a reference point. Thus comparison of the slopes of lines appears to be a second psychological operation available to the mariner, with minimum error when the slopes are equal.

The pilot interviews supported visual angle ratio as an observable, and there is some suggestion in the data from the informal experiment that error was lower at the center for gated than for staggered buoys. The data from the experiment must be treated with caution, since compromises in experimental design were made to minimize cost. The caution must apply both to the difference between gated and staggered buoys in the size of error at the center, and to the similarity between gated and staggered buoys in showing a reference point at the center.

However, pending experiments to provide more precise error measurement, we tentatively propose that both visual angle comparison and slope comparison are performed near the center of the channel. As noted above, we have modeled visual angle comparison by treating the ratio of angles as the observable. We have not yet modeled the slope comparison process.

Buoy Abeam. The third reference point generally coincides with the first in being at the edge of a channel. However, we have treated it as a separate location, rather than as an additional observable for the same location, because it is apparently only applicable when there is a buoy abeam. According to our interview data from Sandy Hook pilots, distance is directly estimated from such buoys. Since distance is more accurately judged for near than for far objects, we have treated the location of the buoy as a reference point.

There are at least two possible observables for estimating distance. One is the visual angle subtended by a single object, which varies with distance. This cue is somewhat problematic, in that error associated with an object of remembered size is unrealistically large. However, it seems possible that a pilot could calibrate his memory at the beginning of a run, or that his extensive experience with distance estimation would make his memory more reliable than occurs in typical experiments. Although the literature on distance estimation is somewhat equivocal, it has been possible to derive a quantitative estimate of the error associated with using visual angle of an object of known size as the observable for distance estimation.

Distance estimates based on objects of known size tend to become slightly large as distance increases; that is, large distances are overestimated. Navigational lore has it that prior to training to overcome the tendency, mariners severely underestimate distances over water. The second possible observable for estimating distance results in underestimation of large distances. That observable is the visual angle

subtended by the distance itself. Our interviews with members of the Pilots Association for the Delaware Bay and River tend to support the view that it is distance itself, rather than the apparent size of a buoy, which is observed. (It seems highly likely that both cues play a role in distance estimation. However, given memory limitations on the use of apparent size, it seems likely that the direct observation of distance will predominate.) The use of the visual angle subtended by the distance itself poses special problems, as it is a subject about which little is known. Dr. Baird, our psychophysics consultant, refers to it as the least well studied of all aspects of visual space. It does appear that some reference length is needed—perhaps the width or the length of the ship—and that error is likely to depend on the reference length as well as on the distance being estimated. We anticipate that experiments will be necessary during Phase II of the contract to determine the error associated with direct distance estimation. For Phase I, we have depended on the error estimate obtained for observing the visual angle of a single object at different distances.

Generality. The three reference points discussed above are points that occur in conventionally-marked straight channels. However, the observables that create those reference points are not restricted to the case studied. We have already remarked that ranges were included under center-of-channel reference points because of their conventional use; the reference point is the on-range position, and it may occur other than in the channel center. In the Panama Canal, for example, ranges mark the center of each half of the channel, providing low error reference at the center of each of two lanes.

It would be presumptuous to assert that no more observables will be found, and foolish to stop looking for them in new situations. At the same time, it is important to note that the observables now under study seem to cover a large number of possible additional cases. For example, our planned study has not included leading lights. Yet leading lights came up in our interviews of Delaware River pilots, in the context

of their explaining their desire that the lighthouses in the lower bay be brighter than they are. Our analysis would have suggested that a single leading light, in contrast to a range, would not be very useful. Our views were confirmed by the fact that pilots do not use the lights alone. Rather, they use them in conjunction with buoys or other aids in a manner described as "like a kind of range." Analytically, if a light is used with a single buoy on one side of the channel, the buoy and the light combined form a range with the on-range position outside the channel. Our analysis of the ability to hold an off-range position should apply. Alternatively, if the light is used in conjunction with two buoys, one on each side of the channel, it creates a pair of visual angles. Now the pilot's task becomes one of maintaining the appropriate ratio of angles or the appropriate combination of slopes. Since this task is the same as using the ratio of visual angles or the combination of slopes to maintain a position near the center of a channel, the error formulas derived for the center-of-channel reference point should apply.

II.B.2.2 Straight Channel: Direction of Motion. *Strategies of Detection*. Our early analysis suggested that direction of motion should be estimated in a derivative fashion, based on observing cross-track location at successive points of advance along the channel. Our interviews with Sandy Hook pilots partially supported that analysis. Pilots made frequent reference to the formula "one hundred feet in one mile equals one degree," and they spoke of adjusting their direction of motion as each successive pair of buoys came abeam. We have followed one of the pilots in designating this explicit computational strategy as "run and observe."

The interviews also indicated that lateral motion could sometimes be directly detected. Although pilots were not able to articulate the cues being used, they were able to tell us that it was easier near the edge of the channel than near the center. It seems clear that "real time detection" is sometimes possible.

A third strategy was hypothesized initially from the needs of the model itself. The model is concerned with the information provided to the mariner at any arbitrarily-chosen point of advance. Run and observe, as originally defined, provided direction information only at buoy pairs, not at any arbitrary point; and real-time detection applies only to relatively large deviations from the desired direction of motion. It seemed necessary, therefore, to suppose that the mariner sometimes notices, at some unspecified point, that his cross-track location is no longer what it should be, whereupon he takes corrective action. Since this approach to detecting direction of motion was viewed as an extension of run and observe to arbitrary points of advance, we have not given it a separate name. In this section it will be called "implicit run and observe," to distinguish it from the explicit preplanned strategy previously discussed.

Implicit Run and Observe. Our model progressed primarily by determining the observables used in estimating a navigation parameter, establishing the error associated with those observables, and propagating that error back into error in the navigational variables. That procedure is clearly applicable to an explicit run and observe procedure: the observables are change in cross-track location, and distance from the last point of observation. For implicit run and observe, the case is not so clear cut. The pilot is presumed to detect an undesirable situation. It is not clear exactly how far back he fixed his position as being acceptable, so both the change in cross-track location and the distance of advance during that change are ill-defined. We have modeled implicit run and observe as a control process, with no explicit estimation of direction of motion. Direction of motion is instead output by the model as a function of the correction process. Interviews with Delaware River pilots suggest this may be appropriate. Those pilots tend not to use the explicit run and observe strategy reported by the Sandy Hook pilots. They indicate that their course adjustment due to discovery that they had moved off-track is a two-stage process: first they move back

to the desired location, choosing a course according to how rapidly they wished to return; then they reestablish a down-the-channel course, not by estimating just how far off their original course was, but rather by a trial and error procedure.

Initial Setting of Direction. The control process we have modeled depends on an initial distribution of directions of motion. The first time it is applied, it must have as input the ability of the navigator to set his direction of motion without reference to external aids to navigation. When we questioned Delaware River pilots on this point, they indicated that they could set their course within one or two degrees, just from knowing the wind and current and the constant error in the gyrocompass. They indicated that only very extreme conditions would induce a deviation of more than two degrees from their desired course.

Real-Time Detection of Direction. The Sandy Hook pilots we interviewed told us that it is sometimes possible to tell that the ship is not moving in the right direction by directly sensing momentary lateral drift. They indicated that they are more likely to sense that drift if the ship is near the edge of the channel and travelling toward that edge.

We have been able to identify only one observable that has even the potential for providing a direct sense of lateral motion. Objects which are fairly near a vessel change bearing at a perceptible rate. If the vessel is progressing directly toward an object, that object will not change bearing, no matter how close it is. The failure of the object to change bearing might not be a sufficient cue, since one would have to recognize not only that it was stationary, but also that it was close enough that it should be changing. In the case of very close objects that should change bearing rapidly, both types of recognition should be possible. But one does not set directly toward very close objects unless one is in serious trouble, and pilots report real-time detection of lateral motion at times when they are not in serious trouble.

There is a plausible way of defining the ability to detect that an object is not changing bearing aft as it should, without requiring that it be too close to be of any use. If the ship is setting, not directly toward an object, but rather slightly toward the wrong side of it, the object's bearing will change forward. If the forward change is at a perceptible rate, there is an immediate and unequivocal indication of motion in an undesired direction. By looking for situations in which an object is perceptibly changing bearing forward, we can determine circumstances which must lead to direct perception of lateral motion.

Examined in the manner described, change of bearing of a single buoy appears to be a qualitatively appropriate observable. It is sensitive to motion toward the channel edge, but not away from it, and it is more sensitive from positions near the edge than from positions nearer the center. Qualitatively, then, it matches pilots' descriptions of their ability to detect lateral motion in real time. There may, however, be some quantitative difficulties, if thresholds for detection of relative motion are computed from available psychological literature. Even from as close to the edge as a hundred feet, there is no location along that edge which should perceptibly change bearing forward unless the ship is travelling toward the edge at an angle of at least two degrees—more, if speed is under ten knots. Since pilots report being able to set direction within two degrees, even without reference to aids to navigation, real-time detection of lateral drift would have to be an extremely rare event. Yet although pilots indicated that real-time detection was only sometimes possible, they did treat it as a normal occurrence.

It is possible, of course, that the Delaware River pilots overestimate their accuracy in setting a course. However, there are two alternative considerations which may account for the apparent quantitative difficulty. The first is that the motion threshold studies we

have found in the literature are concerned with motion of objects toward or away from each other. In contrast, when an object viewed from a ship changes bearing, it appears to move past a point on the ship, not toward or away from it.

The second consideration arises from information provided by the Delaware River pilots. They regard it as quite difficult to detect lateral motion by observing a single buoy, unless that buoy is seen against a background. In essence, they are watching a range of opportunity open, rather than watching an object change bearing. And while any range will open even more slowly than the near object changes bearing, thresholds taken from psychological literature are especially unlikely to apply. The reason is that thresholds have been determined for objects which are initially separated by some moderate visual angle. The value of the threshold is known to vary somewhat with the initial size of the angle. It is likely to be quite small when the initial angle is zero, as it is when one object is directly behind another.

A sample computation will illustrate the contrast between available motion thresholds and those likely to obtain for range objects. We have been using a threshold value for motion a rate of .3 minutes of arc per second, a rate which is detectable only if the observer is allowed 4 seconds of viewing (see Appendix A).
At that rate, the threshold for determining that objects are not on-range would be achieved after only .75 second. The inference is that there is much greater sensitivity to motion for objects on-range than for objects separated from each other.

The foregoing analysis points to a need for accurate data on motion thresholds for opening or closing ranges, with consideration for the vertical separation of the ranged objects. For zero vertical separation, the information will permit modeling of real-time detection of direction based on comparing a buoy with a background. For other separations, the information will be useful in evaluating the ability of ranges, or of buoys which are visually below a landfall, to provide

direct motion sensation. And since the kind of motion involved in an object changing bearing can be thought of as the opening of a range consisting of the object and a point on the ship, it should also improve our understanding of the possible role of isolated objects in providing a real-time indication of lateral motion.

II.B.2.3 Negotiating Channel Bends. Pilots approaching a bend appear to do so with an idea in mind of what rudder angle, or rate of turn, will be appropriate for negotiating the bend, given its configuration and the characteristics of the ship being piloted. When rate of turn is combined with a particular turning point, this is equivalent to selecting a preferred track around the bend. The ability to follow that track will depend on the ability to begin the turn at the proper place, to monitor the progress of the turn once it has started, and to stop the turn in a timely fashion. This appears to apply to both outside and inside turns, since our evidence is that the two types of turns are treated alike.

Initiating Turns. Pilot interview data consistently support the notion that range-type observables are of primary importance in choosing the point to start a turn. In limited visibility, they can choose a point based only on distance to the inside turn buoy. But when asked how they normally negotiate turns, they regularly referred to two types of aids: a range on the new leg, if available, and the combination of the inside turn buoy with the next-ahead buoy. A range establishes a reference point on the center line of the new leg, while the two buoys together, used as a range, establish a reference point on the near edge of the new leg. In general, pilots seem to prefer to use the buoys, but a range is used to check on the accurate placement of those buoys.

When visibility or aid configuration requires the use of the inside turn buoy only, the direct distance estimation process is not different in kind from that used when a buoy is abeam. Direct distance estimation appears to be usable whenever the distance itself is of

interest. In a straight channel, when the navigator is concerned with his distance from the channel edge, that distance is the same as the distance to a buoy only when the buoy is abeam. In making a turn, the relevant distance is distance from the new channel leg, and that distance is approximately the same as the distance to the inside turn buoy. Thus triangulation is not necessary, and direct estimation is used when range-type observables are not available.

Monitoring Turns. Once a turn has been initiated, it is necessary to monitor the rate of turn to be sure that the desired track is being maintained. Errors in rate can arise either from imprecision in anticipating the rate caused by the rudder chosen, or from imprecision in choosing the point to initiate the turn. In the latter case, the rate originally planned will not be appropriate and will require correction.

Three aspects of ship motion appear to be monitored by pilots during turns. The one always explicitly mentioned is the swing of the bow (or of the stern). Swing provides an indication of how fast the ship is turning before any change in direction through the water takes place. It appears to be particularly valuable for that reason: one pilot who reported preferring to watch the stern rather than the bow does so because it starts swinging sooner.

The second aspect of motion that is watched is change in cross-track location in the new channel leg. As the ship turns, motion across the new leg decelerates, and an appropriate rate of deceleration would indicate whether the turn is progressing fast enough. Delaware River pilots, who generally have fairly gentle bends, report getting this information from the aids ahead on the new leg. Sandy Hook pilots were not explicit about this point, but it seems to be part of their reported strategy of maintaining an appropriate distance from the inside turn buoy.

The third aspect of motion being watched was inferred from the close attention paid to the inside turn buoy by the Sandy Hook pilots.

It is cross-track location in the old leg. This needs to be monitored when the turn is sharp, because significant change with respect to the old leg must occur before the new leg is crossed. In gentler bends the ship enters the new leg before any large changes in direction have taken place; this fact presumably accounts for the tendency of the Delaware River pilots to ignore the inside turn buoy in favor of the aids ahead, once the turn has been initiated.

Monitoring turns, like initiating them, depends on observables. For swing, the observable is the apparent motion of objects ahead relative to the bow, or of objects astern if it is the stern that is being monitored. It is not clear whether the concept of reference point is appropriate for the observable for swing. For monitoring changing cross-track location in the new leg, the observables and reference points are the same as for monitoring cross-track location in a straight channel.

For monitoring change in cross-track location in the old leg, the usual observables from the straight channel situation are not available. There is no line of buoys ahead, for example. And since cross-track position is changing, rather than being held constant, it must be integrated with the forward motion of the ship, a process unnecessary in any other case discussed. We are currently treating the bearing of the inside turn buoy as the observable, since geometrical analysis shows that it should be approximately constant during the early stages of a successful turn. Such a cue integrates cross-track location, forward motion, and swing; and holding something constant is in principle a relatively simple psychological task. At the moment we lack human factors data to support this proposed observable; however, John Kemp, our navigation consultant, has suggested that our treatment is appropriate.

Stopping Turns. Although stopping a turn is thought of by pilots as a distinct, separate operation, it appears to depend entirely on the observables for cross-track location in the new channel leg.

Change in location is what pilots report watching. There are complex, visual skills implied in the ability to anticipate the point at which decelerating cross-track location will stop, but the information being used is the same as for implicit-run-and-observe adjustment of direction. The turn is stopped in anticipation of final cross-track location, and the course set will depend on the pilot's ability to anticipate and adjust for wind and current, and on any necessity for correcting final cross-track location. Thus it is possible to treat stopping the turn, not as a third part of the turning process, but rather as a return to a straight channel mode of operation, based on anticipated rather than momentarily perceived location.

II.B.2.4 Other Scenarios. *Coastal, Broad Waterway, and Landfall.* Evidence provided by EASAMS is that coastal navigation is a relatively mechanistic process. Large errors can be tolerated, and navigational strategy involves plotting fixes on a chart. The observables are bearings of objects, as determined with instruments. The errors associated with taking bearings and plotting them have been catalogued by EASAMS, but not measured.

Harbor Entry. The problem of aligning a ship to a channel entrance does not appear to be appreciably different from the problem of turning into a new leg of a channel from a previous one. The chief difference is that, in the absence of the navigational constraints associated with being in a channel, the pilot can hold himself well off the channel entrance, so he need not worry about running over the first buoy on the near edge of the channel. There remains, however, a need to assess the ability to use single objects such as sea buoys for getting in appropriate range of the channel's aids.

Constrictions. Interview data indicate that the observables for approaching constrictions are of the same kinds as are used in traversing a straight channel. Pilots talk about the apparent size (visual angle) of bridge abutments, which are equal when the bridge is approached

from the center, and they talk about ranging on lights on the bridge or on objects of opportunity. Thus constrictions appear to be primarily short sections of unusually narrow channel, subject to the same kind of analysis we have applied to straight channels and channel bends.

Sinuous Channels. Interview data support the notion that a sinuous channel is treated as a series of independent bends. Our analysis of negotiating a bend appears to require only the modification that, instead of stopping a turn by entering a straight channel mode, the pilot must stop it by initiating a new turn. While the knowledge of what rudder will produce what rate of turn may be different (because the ship is already swinging), the information extracted from the A/N should be the same.

II.B.2.5 <u>Navigating in Varying Environmental Conditions</u>. The human factors analysis discussed so far has assumed daytime navigation with reasonably good visibility. Reduction in visibility can, up to a point, be dealt with simply by redefining the aid system available: poor visibility is the same as not having the more distant aids available.

There does not seem to be any strong need to redefine the usability of visual aids for very limited visibility. In interviews, pilots have indicated that they depend on radar when visibility is so bad that they can see aids only part of the time; and with only one set of aids continuously visible, they appear to be able to use the ship superstructure for the ranging and angle-comparing strategies already discussed. Nighttime navigation presents a different problem, because although the aids are visible at considerable distances, they are only intermittently visible. The light characteristics of the buoys that make up a pattern are typically out of phase, so that the pattern used in daytime is never visible in its entirety.

Despite the difficulty caused by intermittent visibility, pilots report "seeing" the same patterns at night that they use in the daytime. Most report that the patterns are harder to see, but there is no indication of any basic change in the kinds of observables being used.

An informal experiment performed on our channel perspective simulator (see Appendix A) provided data consistent with the reports of pilots. Error in estimating cross-track location was consistently larger for intermittently visible buoys than for continuously visible buoys, but it was affected in the same manner by changes in cross-track location.

II.B.2.6 Electronic Aids. Pilots indicate that, at night, they use radar to supplement and confirm visual navigation. In particular, they use it to check on the distance of aids, which may be visible from much greater distances at night than during daylight hours under comparable conditions of visibility. Radar becomes a primary means of navigation only when visibility is poor. When it is necessary to pass one aid before the next one comes into view, position and direction of motion are obtained from radar, and visual checks serve merely to confirm the correctness of actions already taken.

Preliminary analysis of the use of radar suggests two modes of operation. The navigator may obtain his position by using the radar to obtain range and bearing, or he may directly interpret the PPI display by visual inspection. By analogy with the use of visual aids, we assumed for Phase I that distance was measured when it was directly of interest and did not have to be combined with bearing to establish a position. This means that distance would be measured to an inside turn buoy to establish the point for a turn, or that it would be measured to a buoy abeam in a straight channel. At other times, we assumed that the operator visually estimates his position with respect to the lines formed by buoys along the side of the channel. Based on this analysis, we regard distances along the radar graticule to be the basic observables, with error generated by incomplete adjustment for slant range and by perceptual limitations in estimating short distances. Although we are satisfied that the principles of analysis used for visual aids can be applied to a PPI display, the actual observables and errors modeled are at this point merely plausible guesses.

Although a first cut was made at modeling information from LORAN-C, human factors errors were not treated. We assumed that a prudent mariner would not use LORAN-C except as a supplementary aid in a restricted waterway, unless fixed errors were eliminated or compensated for. Fixed errors are primarily attributable to survey errors, the difference between true earth geometry and the ellipsoid used in calculating time delay hyperboles, and differences between actual and calculated propagation velocities for overland portions of the transmission path. Entered into the model were errors resulting from instabilities in the transmitting system and receiving system and from atmospheric noise levels. An important candidate for future human factors consideration is the time delay between obtaining a reading and plotting it.

II.B.3 Modeling of Information from A/N Systems

A basic navigation process for straight channels and bends is the run and observe process, using successive position fixes (cross-track position for straight channels). This assertion was both suggested by and substantiated by the series of pilot interviews, discussed in Section II.B.2. The utilization of this process appears to be relatively independent of the type of A/N available to the mariner. However, the precision with which the run and observe process can be accomplished will, of course, depend on the precision with which the position fixes can be obtained from a given A/N system.

For straight channels, the ability to accomplish run and observe depends on the ability to fix cross-track position. Because of the difficulty of observing motion directly for most reasonable ship speeds in confined waterways, both of the straight channel navigation variables (cross-track position and direction of motion) appear to be set by successive observations of cross-track position (Appendix B discusses the difficulty of fixing direction of motion real-time using visual A/N).

A variation of the run and observe process is used in completing bends also. In particular, monitoring the progress of a turn is essentially a run and observe process.

We have developed a computerized model of the run and observe process. Outputs from this model are used in the portion of the risk methodology that requires characterization of the ability to navigate using information from a specified A/N system.

The straight channel run and observe model requires as input errors which reflect the ability to fix cross-track position in the channel. The mariner's ability to accomplish run and observe is dependent on these errors. In addition to the above errors, the bend model characterizes the effect on the turn process of errors in point-to-turn and the uncertainty inherent in using the A/N to monitor the turn.

II.B.3.1 Generation of Error Maps. Error maps representing a pilot's ability to fix his cross-track position are input into the run and observe model. These error maps characterize the cross-track position information the pilot receives from the A/N system. The pilot is assumed to be located at the center of the vessel. The error maps in Phase I were developed considering the pilot at center of the ship and the height of the vessel which modifies the uncertainty in cross-track position for some A/N systems. Error maps for the straight channel are express in terms of the standard deviation in cross-track position, σ_p, for a given A/N system. The process of generating error maps involves the following steps:

- Identify the observables used by mariners for the A/N system(s) under analysis. Essentially, this is a human factors job. During Phase I, this was accomplished by structured interviews of pilots. More than one observable may be used and there may be different observables used in different parts of the channel. However, we have found only a very limited set of observables that are used over and over again for a variety of A/N and in a variety of contexts. Examples of observables are the alignment of objects (ranging); the matching of visual angles or apparent slopes (gated or staggered buoys); direct distance estimates; bearing or bearing rate observations, and the apparent slope of lines formed by the perspective view of, for instance, buoys marking the channel edge. See Section II.B.2 for a more detailed discussion.

- Relate the observables to the navigation variable. For straight channels, the navigation variable of interest is cross-track position, and the observables usually give information about this variable. Constructing this relationship involves a consideration of the reference point for the navigation variable, and the change in the observable on moving from the reference point. The result is an error equation

relating the observable and the navigation variable. Example error equations for the A/N cases analyzed during Phase I are presented in Appendix B.

- The next task is to characterize the error in the observable so that this can be propagated to obtain the error in cross-track position (σ_p). The error in the observables was characterized based on available information in the psychological literature, and using the reference points to establish where the error is a minimum. In Phase I, the combination of information in the literature and arguments of reasonableness concerning how the errors should change in excursions from the reference point was used to establish the error in the mariner's ability to fix cross-track position (σ_p). The σ_p's generated in this way are thought to be reasonably accurate, but generating and checking these numbers using human factors experiments is a high priority task for Phase II.

- Finally, routine error propagation is used to obtain the error map in terms of σ_p's. Two techniques were used during Phase I: generalized least squares and Monte Carlo simulation. The Monte Carlo method was required in some cases because the errors in the observables were not normally distributed and thus not amenable to the generalized least squares method. The change of error in the observable in excursions about the reference point for these cases results in skewed distributions for errors in cross-track position. Appendix B discusses this in some detail. For Phase I, however, skewness was ignored in the generation of the error maps (except to note that it exists). Including skewness in the error maps, and treating this in the run and observe model, are high-priority tasks for Phase II.

The end result is a map of errors in the navigation variables which is displayed on the channel. For straight channels, this is referred to as a σ_p map. Figure II-1 is an example of a σ_p map for a channel marked with gated buoys. Three zones are identified corresponding to the observable that would be used to fix cross-track position in that zone. The σ_p's in zone 1 were obtained by propagating errors in the mariner's ability to fix cross-track position by matching visual angles. Zone 2 reflects the mariner's ability to fix cross-track position using the apparent slope of the line formed by the perspective view of the buoys on the near side. Zone 3 reflects direct distance estimation to the buoy abeam. The error maps for all cases analyzed are presented in Section II.C.

The technique for generating (and using) error maps is completely general and applies to arbitrary systems of visual or radio aids.

The error maps are input to the run and observe model, discussed in the next section.

II.B.3.2 Straight Channel Model. The run and observe model for straight channels is a control theory model where control is provided by the A/N. That is, the ability to fix cross-track position using the A/N is the control provided for navigating the channel. The mariner establishes direction of motion by reference to successive fixes of cross-track position. The σ_p map (previous section) reflects the mariner's ability to fix cross-track position, and provides the control function for the model. The inputs to the model are the σ_p map, the desired track, and the navigator's band of indifference. The outputs are distributions of cross-track position and direction of motion at arbitrarily specified places along the channel. These distributions reflect the variation in ship position and movement that result from ambiguities and uncertainties in the information provided to the mariner by the A/N system under assessment. Thus, differences between A/N systems are made apparent.

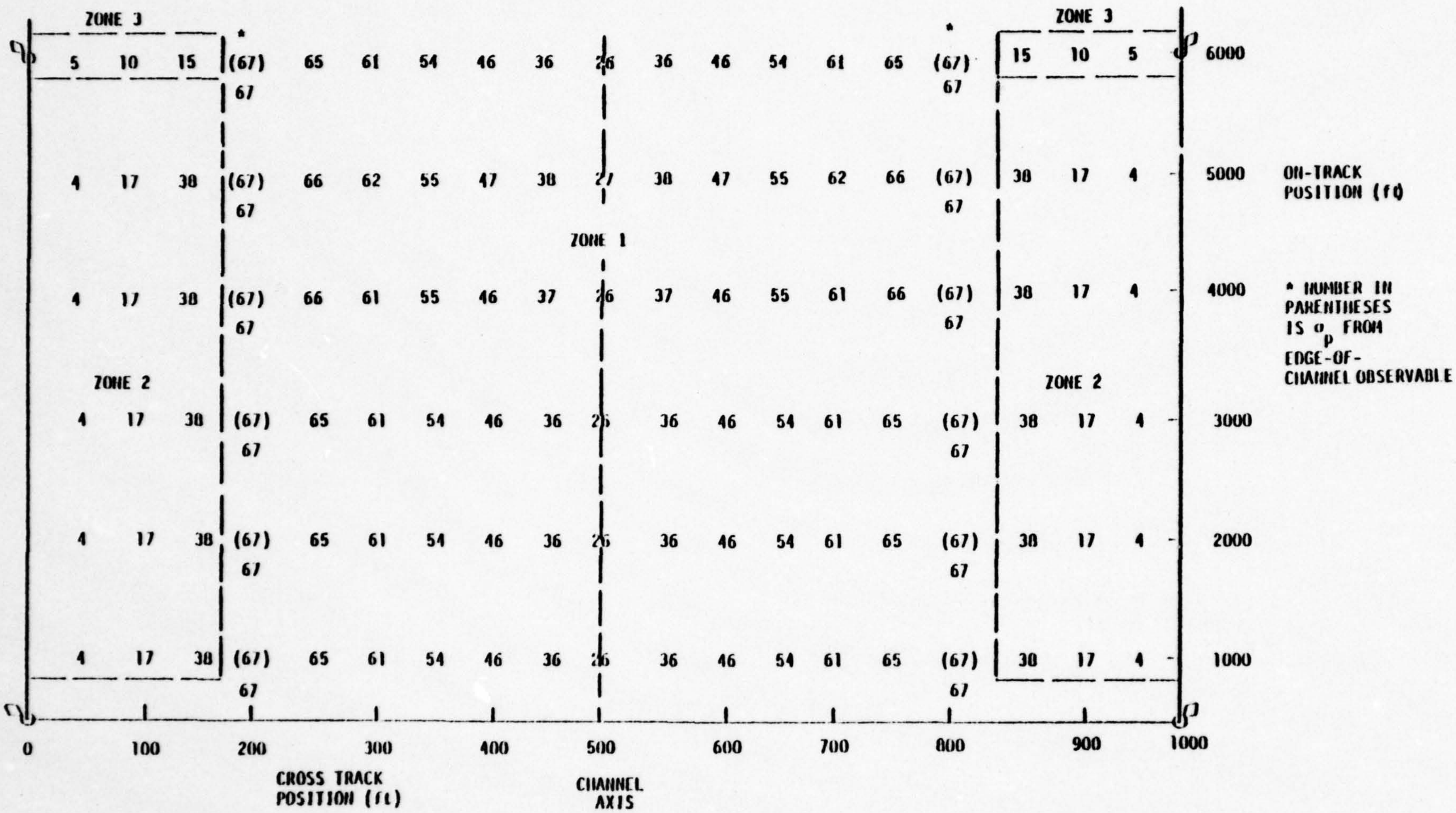

FIGURE II-1. σ_p MAP, GATED BUOYS

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The run and observe model consists of the major functional blocks illustrated in Figure II-2. These blocks are:

- The initial conditions, which can be formulated to represent a distribution of cross-track positions and directions of motion that would correspond to the values resulting from channel alignment and/or from an uncompensated-for wind/current. In general, the initial conditions will result in a transient region upon entering the channel that reflects the information provided to the mariner to correct for uncompensated wind/current, or inaccurate channel alignment.
- The σ_p map for the A/N system, which provides the control for the model.
- The decision module, which uses the statistics provided by the σ_p map to specify portions of ships having a distribution of cross-track positions and directions of motion that will decide that they are too far from the intended track and wish to make a correction. These ships will undergo course changes to correct to positions closer to the intended track. Part of the decision function is a specifiable region of indifference about the intended track. Mariners will not make corrections if they perceive themselves to be in this region. They will make corrections only if they perceive themselves to have left this region.
- The course correction module, which applies a two-course correction to that portion of the distribution of ships that the decision module specified to have perceived themselves as having left the indifference region. The present model simply distributes the ships making corrections over a range of cross-track positions consistent

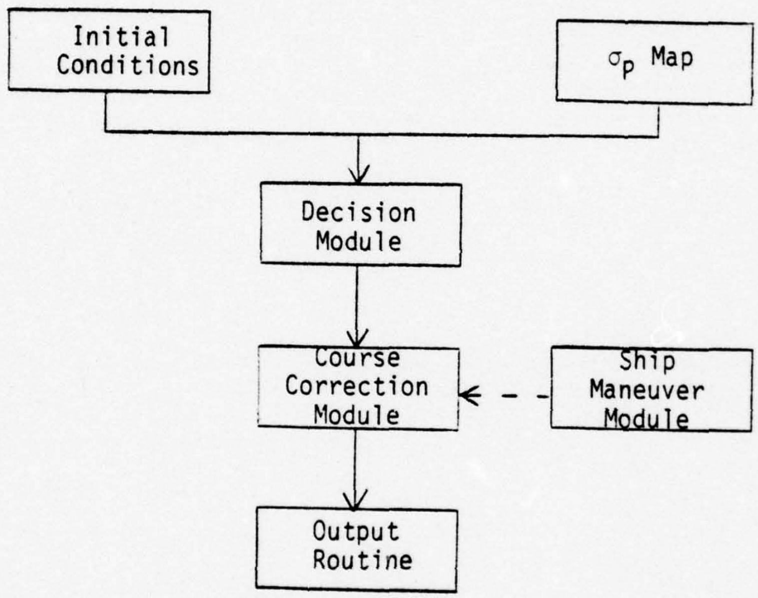

FIGURE II-2. MAJOR FUNCTIONAL BLOCKS—RUN & OBSERVE MODEL

with the σ_p map; and having a range of directions of motion somewhat reduced from the range of directions of motion before the correction (this reflects the mariner's ability to learn about his ship's direction of motion from the series of past observations, and correct to values closer to the desired value). In the Phase I model this course correction procedure takes 1200 ft., which is arbitrarily specified. Figure II-2 also shows an intended refinement of the model, which would use actual simulated ship movements derived from the ship maneuver model (Appendix B and later sections discuss the ship maneuver model) to make the course corrections. This is a high-priority item of future work for Phase II.

- Output from the model consists of distributions of cross-track positions and directions of motion that reflect the ambiguity and uncertainty resulting from using information from the A/N system to navigate the straight channel.

Further discussion of the Phase I model is presented in Appendix B. Discussion of intended Phase II improvements and refinements to this model are presented in Section III.A.

II.B.3.3 Bend Model. In addition to cross-track position and direction of motion, navigating a bend requires information concerning the point to initiate the turn, information for monitoring the progress of the turn after the initial rudder has been set, and information to assist in steadying on the new course. For the purposes of the model, the bend navigation scenario is defined to include the initial rudder commands to initiate the turn, monitoring of the progress of the turn, and the rudder amidships command; the task of steady on the new course is defined as the initial straight channel task for the new straight channel segment.

Input to the bend model includes the physical characteristics of the bend (old and new channel courses); the intended ship's track around the bend; a distribution of cross-track positions and ship directions of motion going into the bend (i.e., at the position of the initial rudder command); a distribution of on-track positions reflecting the mariner's ability to perceive the point to initiate the turn using the information from the A/N, and a distribution reflecting errors in the ability to use the A/N to monitor the turn. The output from the bend model is a distribution of cross-track positions and ship's directions of motion in the new channel, which is used as initialization for the new straight channel navigation task. This output would initialize the straight channel run and observe model for the new channel segment. The distribution of cross-track positions and ship directions of motion used to initialize the bend model would have been obtained from the output of the straight channel run and observe model operating on the old leg. Thus, the bend model meshes with the run and observe model to connect succeeding straight channel segments.

Figure II-3 illustrates the primary functions of the bend model. Like the run and observe model, the bend model uses a finite difference solution technique to perform the required transformations of the various distributions in the model to the output distribution of cross-track position and ship direction of motion. The bend model functions are:

- The straight channel run and observe model for the old channel supplies the initial distribution of cross-track position (P) and ship's direction of motion (θ) to the bend model.
- Pilots have different strategies for executing the bend maneuver, which are essentially trade-offs between how early the turn is initiated and the degree of initial rudder applied. Only a limited range of strategies

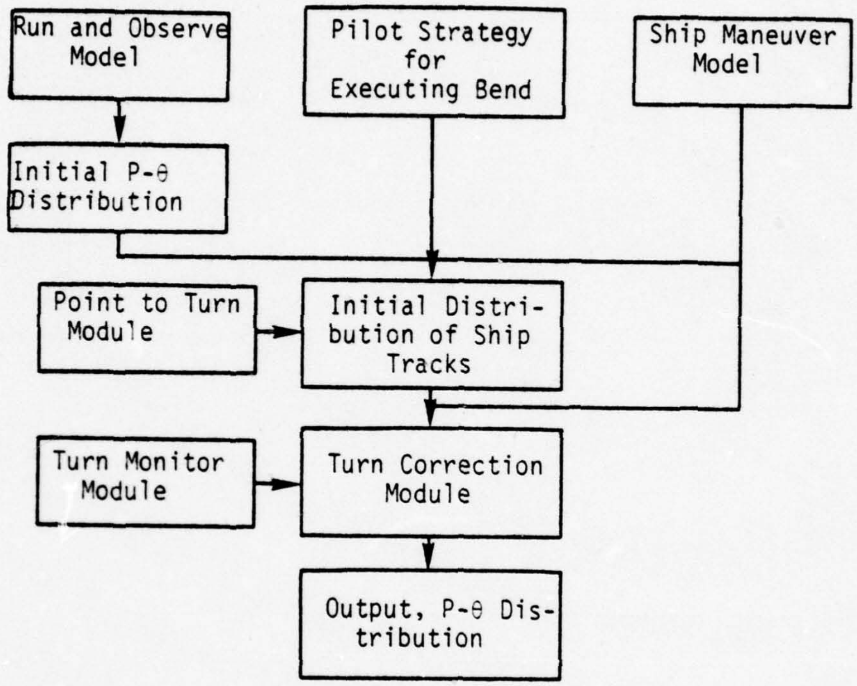

FIGURE II-3. BEND MODEL FUNCTIONS

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is permitted in the Phase I bend model. Increasing the number of permitted bend strategies is a high-priority item for Phase II.

- An initial distribution of ship tracks around the bend is generated using the ship maneuver model with initial conditions of direction of motion and position specified by the initial P-θ distribution, the distribution of on-track positions resulting from the point-to-turn module, and the specification of the pilot strategy for executing the turn. The point-to-turn module develops a distribution of on-track position from the information available from the A/N. The Phase I model uses the visual angle subtended by the inside-turn buoy and the next-ahead buoy on the new channel as the observable for point to turn (see Section II.B.2).

- Monitoring of the turn is accomplished by the turn monitor module. The initial distribution of ship tracks is altered based on the portion of ships that decide that the progress of the turn is not correct. The function of the turn monitor module is to specify that position. The function of the turn correction module is to alter the ship tracks of the portion of ships that are correcting. The altered ship tracks are corrected using the ship maneuver model. In the Phase I model, the observable for monitoring the turn is the observed bearing change to the inside turn buoy.

- The output of the bend model is a distribution of cross-track positions and directions of motion in the new channel. This distribution can be used as the initial distribution for the straight channel run and observe model for the new channel.

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A more detailed discussion of the Phase I bend model is presented in Appendix B. Planned improvements to this model, which would be accomplished in Phase II, are discussed in Section III.A.2.

II.B.4 Derivation of Safe and Grounding Domains

Grounding domains are constraints on the navigation variables.

Grounding domains are composed of all combinations of values for the navigation variables that result in the vessel going aground -- no matter what actions are taken by the mariner. Values of the navigation variables that lie within the grounding domain imply that it is physically impossible to prevent the vessel from grounding. Safe domains complement grounding domains. Safe domains are composed of all combinations of values for the navigation variables for which the mariner could prevent the vessel from grounding.

Parameters that can modify the grounding domain of a vessel include speed of the vessel, ship type, characteristics of the waterway such as shape of bank or depth of water. Wind and current can also change the vessels grounding domain. The grounding domains are defined using parameters that are completely independent of the aid to navigation system. Changing the aid to navigation system will not affect any change to the grounding domain of the vessel.

The most important navigation variables were used to develop the grounding domain methodology in Phase I. Many parameters that can modify the grounding domain and should be considered were ignored during Phase I in order to expedite the human factors modeling.

Safe and grounding domains examples were developed for a straight channel and for a channel bend.

Two ship types were utilized in the straight channel scenario. The two ships were an 80,000 DWT tanker and a 250,000 DWT tanker. The channel bend example was completed for the 80,000 DWT tanker.

Straight channel navigation variables considered during Phase I were cross-track position and direction of motion of the vessel.

Values of straight channel navigation variables that fall within the grounding domain of an 80,000 DWT tanker are illustrated in Figure II-4. Ship #1, in Figure II-4, was located 200 feet to the left of the ideal track; any angle of deviation greater than or equal to 14^{o} to the left of the ideal track would guarantee grounding of the vessel. Ship #2 was located on the ideal track; any angle of deviation greater than or equal to 22^{o} to the right or to the left of the ideal track would guarantee grounding of the vessel. Ship #3 was located 100 feet to the right of the ideal track; any angle of deviation greater than or equal to 18^{o} to the right would guarantee grounding of the vessel.

Figure II-5 illustrated all conditions that guarantee grounding for an 80,000 DWT tanker in a 1,000 foot wide straight channel. The calculations for the grounding domains as shown in Figure II-5 did not include current, depth of channel, suction, or cushion; these factors would be incorporated in subsequent refinements of the grounding domain model.

An analogy can be made between Figure II-4 and Figure II-5. Ship #1 in Figure II-4 illustrated the same grounding conditions as point M in Figure II-5. The conditions of ship #1 and the coordinates of point M each state that grounding of our 80,000 DWT tanker will occur when it is 200 feet to the left of the ideal track and has an angle of deviation to the left of the ideal track greater than or equal to 14^{o}. Point N and point O, respectively in Figure II-5, are equivalent to the conditions of ship #2 and ship #3 in Figure II-4. Point P (800, 18^{o}) serves to illustrate that once a grounding angle has been achieved, any larger angle of deviation would likewise cause a grounding.

Figure II-5 is a graphical representation of the grounding domains that guarantee the grounding of an 80,000 DWT tanker under the assumptions as previously stated. Values of the straight channel navigation

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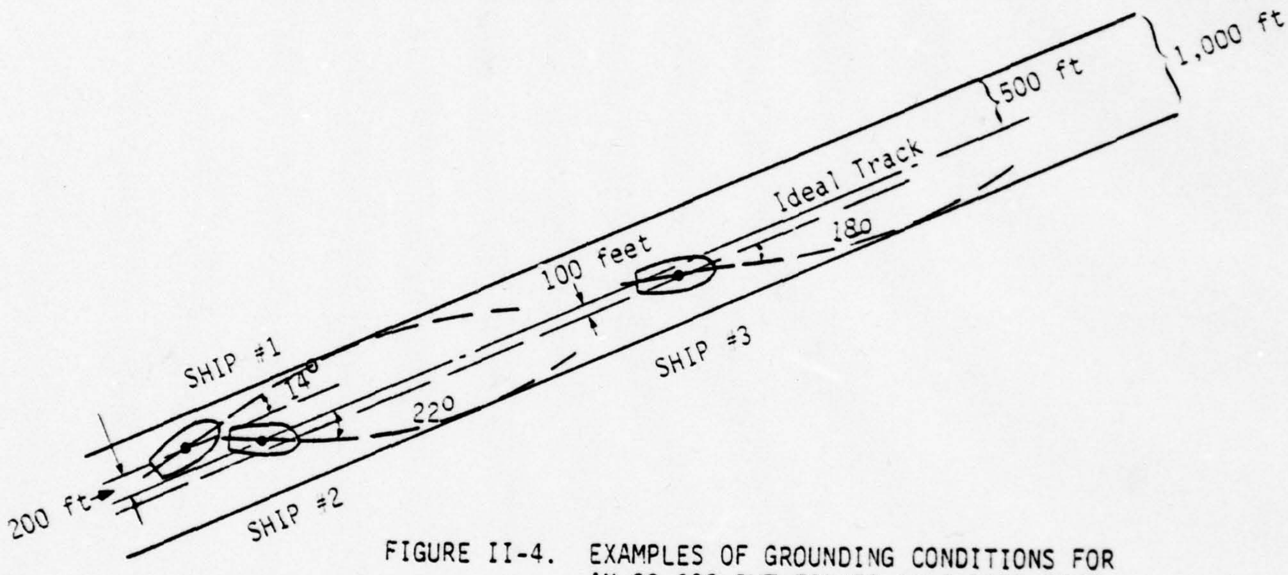

FIGURE II-4. EXAMPLES OF GROUNDING CONDITIONS FOR AN 80,000 DWT TANKER IN A 1000 FOOT-WIDE CHANNEL

Straight Channel Grounding Domain Example

80,000 DWT tanker
8 knots
current/wind = 0

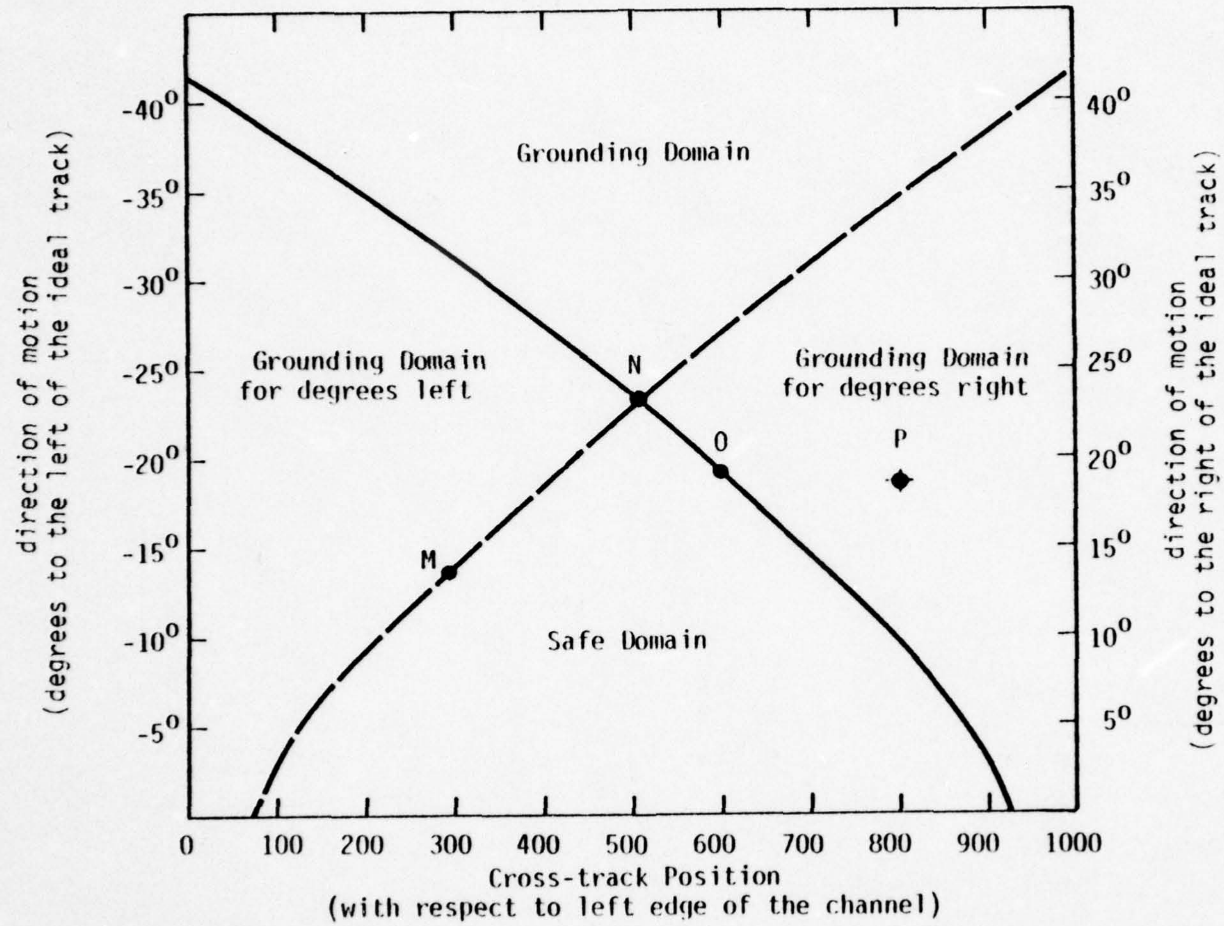

FIGURE II-5. GROUNDING DOMAINS FOR 80,000 DWT TANKER IN A 1000 FOOT-WIDE CHANNEL

variables that correspond to points under the dashed curve will not ground against the left edge of the channel, and values of the navigation variables that correspond to points on the dashed curve or above it indicate that the vessel will ground. Similarly, values for navigation variables that lie below the solid curve indicate that the vessel will not ground against the right edge of the channel, while those points above or on the solid curve indicate that grounding will occur. These results will be used to illustrate a measure of risk in the next section.

A second example vessel was a 250,000 DWT tanker. Grounding domain values for a 250,000 DWT tanker traversing a 1000 foot wide channel are shown in Figure II-6. Comparison of the grounding domains associated with an 80,000 DWT tanker (Figure II-5) and the 250,000 DWT tanker (Figure II-6) illustrates that the 250,000 DWT tanker requires more distance to correct errors in the vessel's direction of motion. The additional distance needed for correcting the 250,000 DWT direction of motion errors will contribute to increased risk when traveling in confined waterways.

The navigation variables for channel bends include angular velocity of the vessel and along-track position, as well as cross-track position and direction of motion. The large changes in direction of motion while negotiating a bend required that angular velocity be included as a channel bend navigation variable.

Appendix B.II presents a detailed discussion of grounding domains for channel bends. The appendix includes illustrative examples as well as calculation techniques utilized.

Straight Channel Grounding Domain, Example 2

250,000 DWT Tanker
8 knots
current/wind = 0

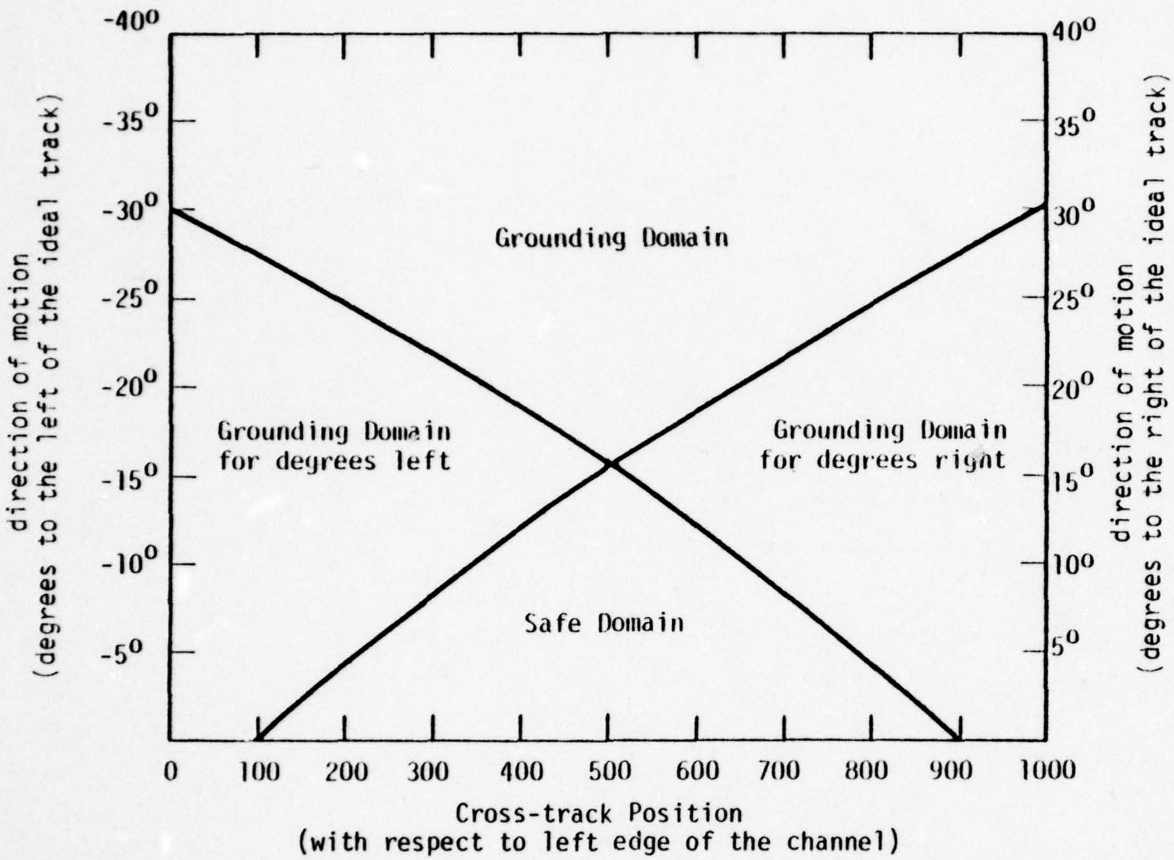

FIGURE II-6. 250,000 DWT TANKER GROUNDING DOMAIN EXAMPLE

II.B.5 Measure of Risk. Pilot decision time and pilot indifference region have been identified as measures of risk during Phase I. Pilot decision time expresses the time that a pilot has before a course correction is necessary to avoid grounding. The indifference region characterizes the stress on the pilot to maintain cross-track positions near the ideal track.

Pilot decision times were defined by comparing the joint distributions of cross-track positions and directions of motion to the grounding domain of the vessel. Joint distributions of cross-track position and directions of motion were discussed in some detail in Section II.3.2 of this report. The grounding domains were discussed in Section II.4 of this report. Pilot decision times were evaluated for 1000 vessels traversing a straight channel. The integrated pilot decision times provided a probability density function as shown in Figure II-7. This probability density function was used to define a cumulative probability distribution for pilot decision times of varying sizes. Figure II-8 illustrates the cumulative distribution of pilot decision times developed by using the data in Figure II-7. Cumulative distributions similar to the one shown in Figure II-8 were developed at 1500 foot intervals after the vessel's navigation variables were under the influence of the specified A/N system. The frequency of vessels that had pilot decision times less than or equal to fifteen minutes was extracted at each 1500 foot interval. These results are shown in Figure II-9. The rate that the frequencies decrease while under the influence of a particular A/N system is a measure of the system's effectiveness. The comparison and interpretations of this measure of effectiveness will be discussed in detail for various A/N systems in Section II.C of this report.

The concept of an indifference region is a measure that will be developed in Phase II and was discussed in Section III.2 of this report.

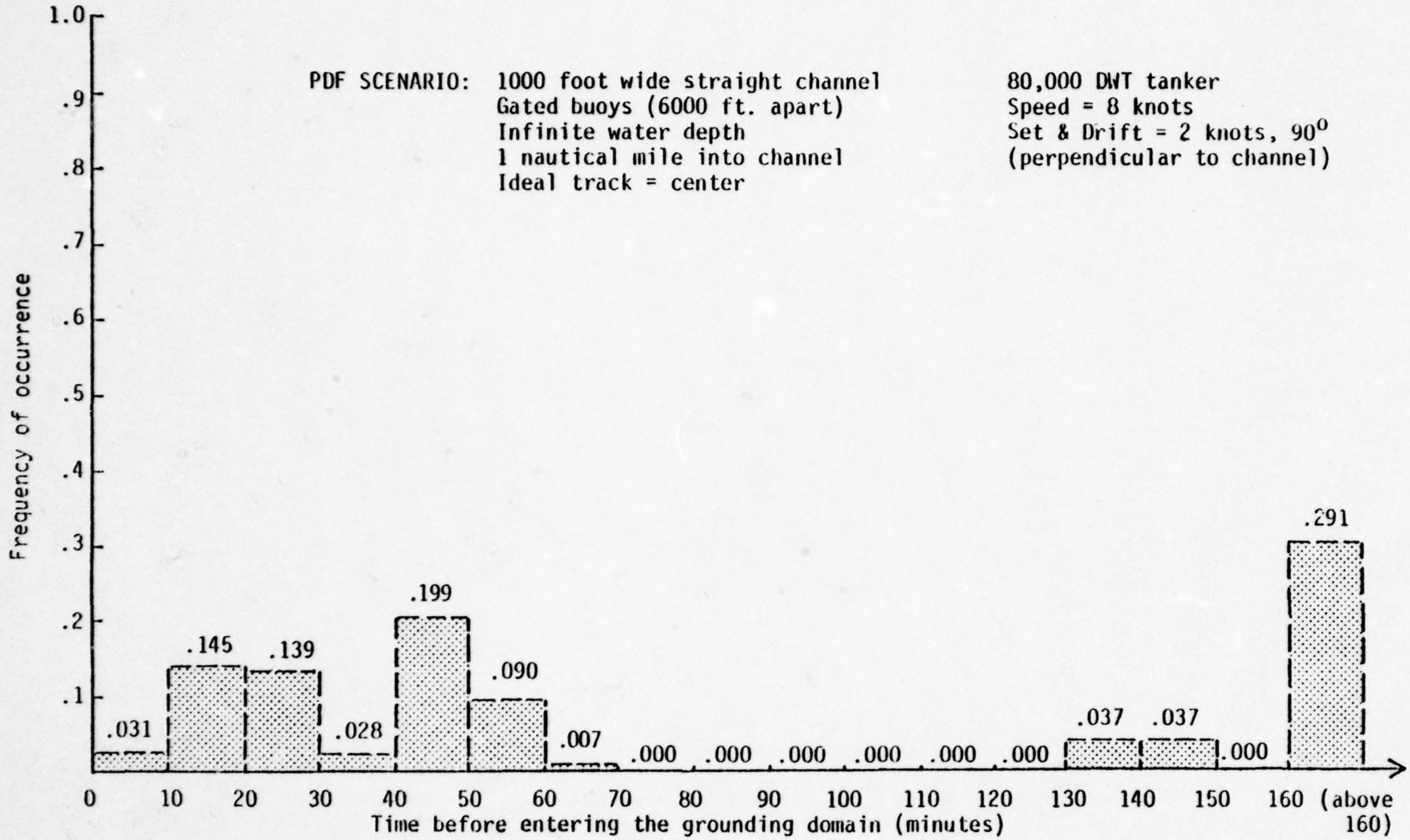

FIGURE II-7. EXAMPLE OF A PROBABILITY DENSITY FUNCTION FOR PILOT DECISION TIME

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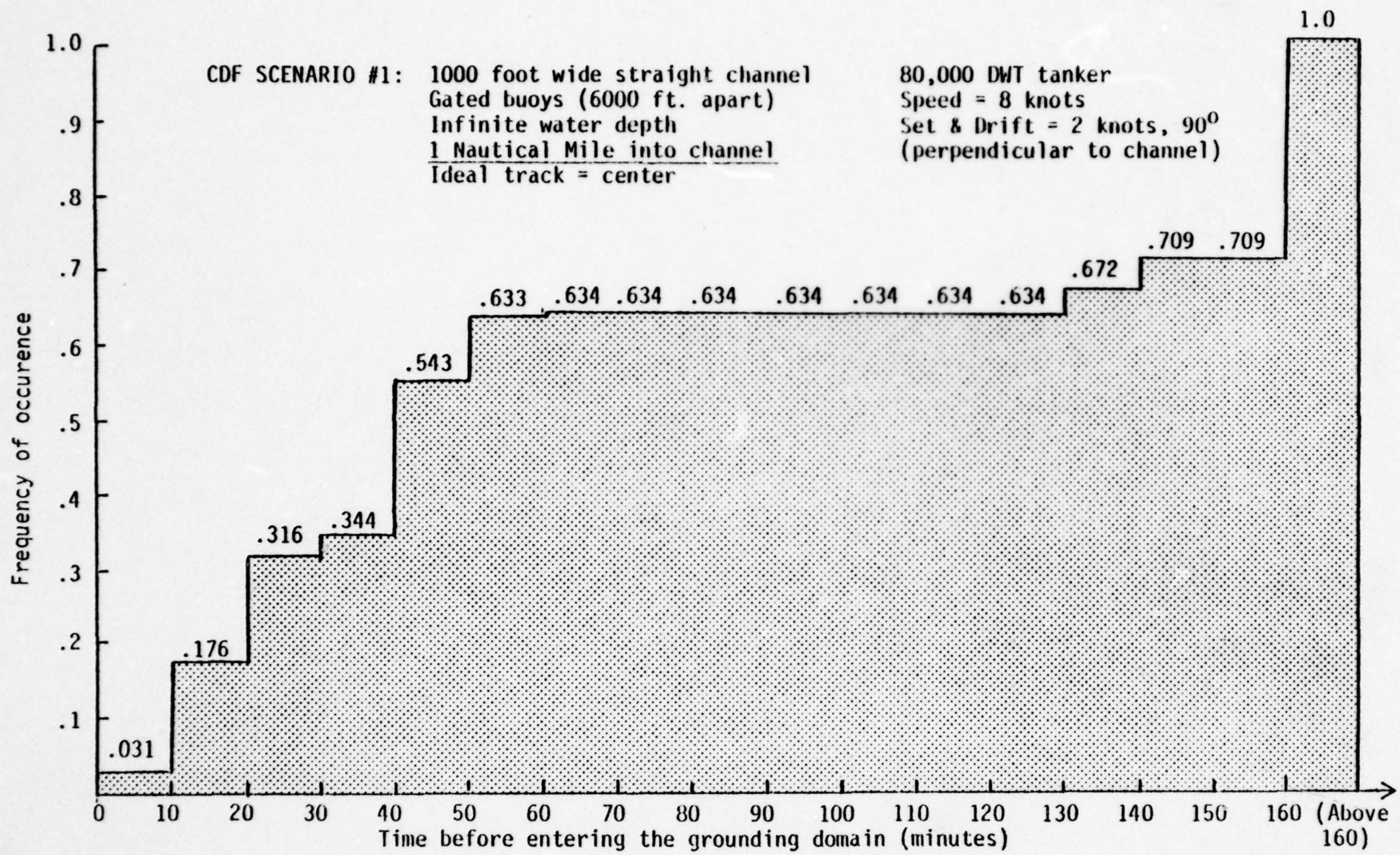

FIGURE II-8. CUMULATIVE PROBABILITY DISTRIBUTION FOR PILOT DECISION TIMES, EXAMPLE #1

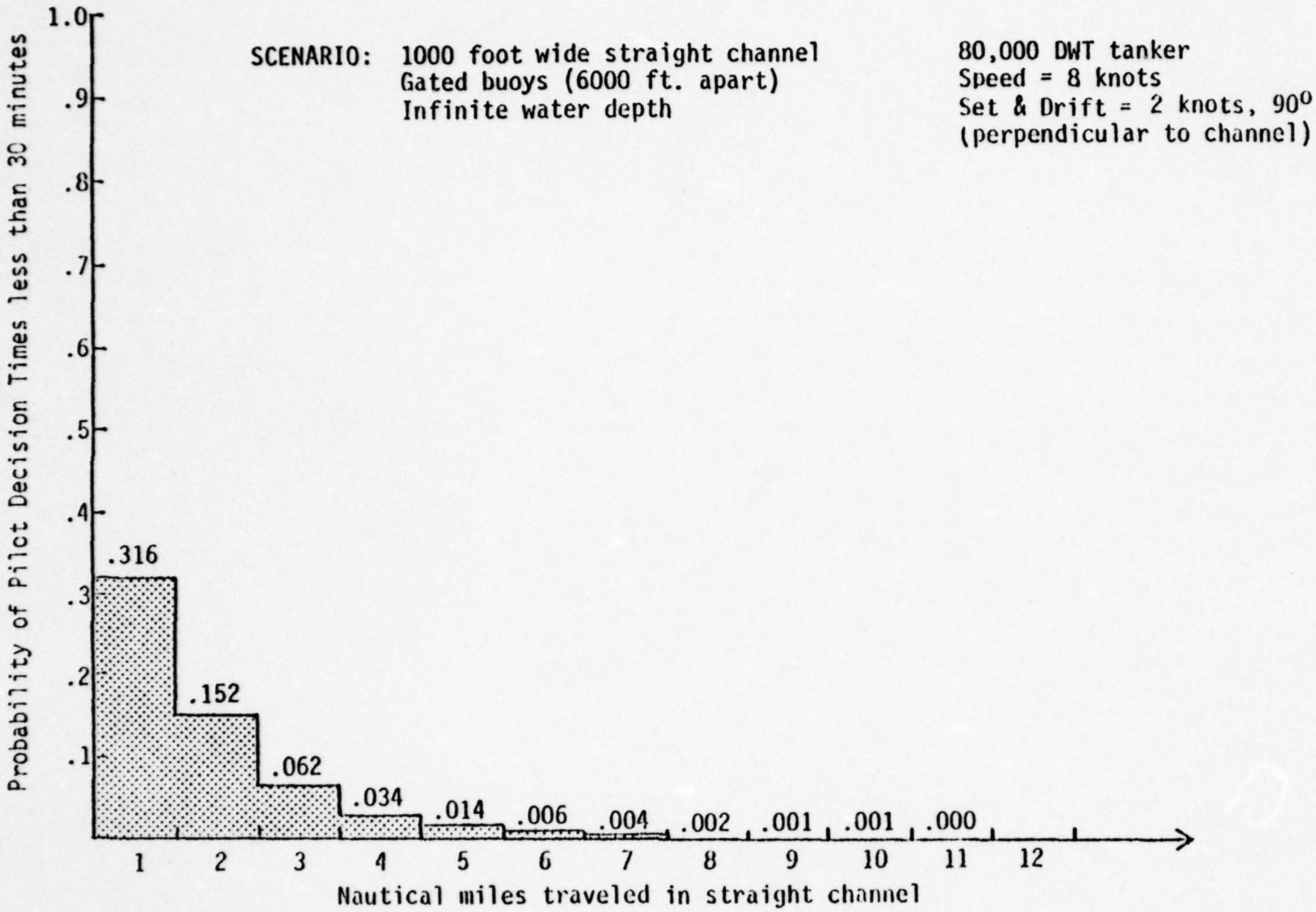

FIGURE II-9. REDUCTION OF RISK EFFECTIVENESS FOR GATED BUOYS

II.B.6 Phase I Integrated Model

The models described in the foregoing have been integrated into a preliminary Aids to Navigation Risk Model. This integrated model consists of the following submodels:

- Run and Observe Model for straight channels.
- The Bend Model.
- The Safe/grounding Domain Model.
- The Measure of Risk Model.

Each of the submodels is incomplete and will require refinements, improvements, or extensions in Phase II. A few of the planned improvements were discussed in the previous sections, and are elaborated on in Section III. The total integrated model will require extensions to handle other navigation scenarios, e.g., the constriction scenario. However, the present integrated model is capable of running through a complete problem where each of the submodels is exercised. Section II.D presents such an example problem.

II.C. Comparative Results

The preliminary results for various aid to navigation systems are shown at the end of this section in Exhibits 1 through 17. A summary table of these outputs is shown in Table II-1. The model outputs shown in the exhibits are:

1. Cross-track position contours
2. Direction of motion contours
3. *Improvement in pilot decision times.*

The interrelationships of these three outputs with the particular aid to navigation system being utilized by the pilots provides insight into the effectiveness of that aid to navigation system. Comparison of the three model outputs described above for various identical desired tracks, while maintaining the ship type, ship speed, environmental conditions, waterway geometry, etc., shows the effect of the information provided by different aids to navigation systems. In a similar way, the model was shown to be sensitive to ship type, desired track of the vessel, visibility, and the pilot indifference zone. The corresponding σ_p maps used for the exhibited cases are shown in the figures listed below:

Gated Buoys (Cases 1,2,3,17)	Figure B-20.a
Buoys One Side (Cases 4,5,11,12)	Figure B-21.a
Range Only (Cases 6,7,8)	Figure B-22.a
Range/Buoys One Side (Cases 9,10)	Figure B-23.a
Radar (Case 15)	Figure B-25.a
LORAN-C (Case 16)	Figure B-26.a
Buoys One Side/Poor Visibility (Cases 13,14)	Figure B-24.a

For convenience of the reader, these figures are shown right after the exhibits in this section.

The preliminary results shown in Exhibit 1 for gated buoys will be used to illustrate interpretations that can be made from the

model output. The buoys shown are symbolic of buoys located on the channel edge. Buoys are located on both sides of the channel and the buoys are gated. This information is shown to allow correlation of the changes in models output to the aid to navigation system. Runs were initiated with 1000 vessels whose directions of motion were uniformly distributed from .2 degrees to the left (top of figure) to 3.4 degrees to the left. The initial cross-track positions of all runs were uniformly distributed from 50 feet to the left of the ideal track to 50 feet to the right of the desired track. All cases were run at 8 knots initial speed, indifference zones of 25 feet, ship type of 80,000 DWT tanker, unless otherwise specified in the exhibit.

The cross-track information is displayed as probability contours. The dashed curves in Exhibit 1 bound 98 percent of the cross-track positions that vessels could maintain while traversing a channel of this size. The solid curves in Exhibit 1 bound 80 percent of the cross-track positions that vessels could maintain while traversing a channel of this size. The initial conditions could result in a transient region for cross-track position and direction of motion until the pilots perceive their cross-track positions as being incorrect and change their course. Several course changes may be required before this transient region is damped by the information from the aid to navigation system. The time period or distance that is required to reduce the initial transient to zero is referred to as the transient portion of our output. This transient portion characterizes the effectiveness of the information from the A/N system to dampen incorrect directions of motion. For the gated buoy case, the transient portion of the run damps to steady-state at about 2 nautical miles. The transient region will be used when comparing different A/N systems.

The portion of the run after 2 nautical miles shows a rather steady pattern for cross-track position as well as directions of motion. This portion of the run will be called the steady-state portion of the run. The portion of the run will be used to compare different A/N systems.

The direction of motion contours are analogous to the cross-track contours. The dashed curves bound 98 percent of the directions of motion, while the solid curves bound 80 percent of the directions of motion. This information can be used to correlate changes in direction to the information in the A/N system.

The degree of improvement in pilot decision times is also shown in each exhibit and will be used to compare different A/N systems.

II.C.1 Gated Buoy vs Range Comparison

The first comparison to be made will be utilization of gated buoys for traversing a desired track down the center of the straight channel as compared to a range. The gated buoys are spaced every nautical mile. The front range beacon is located 6 miles from the starting location of the vessel, and the beacon spacing is 1 mile.

Exhibit 1, Gated Buoys. The cross-track positions stabilize after a transient distance of about 2 nautical miles. There appears to be no noticeable effect when passing a buoy; this results from modeling visual angle matching as the observable in the center of the channel. The magnitude of the 98 percent bound for directions of motion is $\pm 4^{\circ}$. This is due to the cross-track distance at which the pilot perceives his cross-track position as being incorrect. The 98 percent bound on cross-track positions stabilizes at $\pm$ 80 feet. The risk level is maintained at less than 10 persent of the vessels with pilot decision times less than 15 minutes.

Exhibit 6, Range Only. The cross-track positions improve as the vessels approach the range. The magnitude of the 98 percent bound for cross-track positions decreases to $\pm$ 30 feet as the vessels approach the range. The magnitude of the 98 percent bound for directions of motion improve as the vessels approach the range due to improved cross-track information. The number of vessels having pilot decision times less than 15 minutes decreases as the vessels approach the range.

II.C.2 Pilot Indifference Comparison

Different pilots have different cross-track locations away from the ideal track at which they choose to change their direction of motion so as to return to their desired track. The first exhibit discussed below illustrates the results when a pilot does not correct until he perceives his location as being 25 feet from his desired track. The second exhibit discussed below illustrates the results when a pilot corrects whenever he perceives his location to have deviated from the desired track by any amount.

Exhibit 1, 25 Foot Indifference. The cross-track positions stabilize after a transient distance of about 2 nautical miles. There appears to be no noticeable effect when passing a buoy; this results from modeling visual angle matching as the observable in the center of the channel. The magnitude of the 98 percent bound for directions of motion is $\pm 4^{\circ}$. This is due to cross-track distance at which the pilot perceives his cross-track position as being incorrect. The 98 percent bound on cross-track positions stabilizes at $\pm$ 80 feet. The risk levels off, such that less than 10 percent of the vessels maintain pilot decision times less than 15 minutes.

Exhibit 2, 1 Foot Indifference. The cross-track positions stabilize in less than one nautical mile. There appears to be no noticeable effect on cross-track position when passing a buoy; this results from modeling visual angle matching when near the center of the channel. The magnitude of the 98 percent bound on directions of motion is slightly less than the 25 feet indifference case due to correcting as soon as the pilot perceives he is not on the desired track. The number of vessels having pilot decision times less than or equal to 15 minutes is maintained at less than 10 percent.

II.C.3 Visibility Comparison

The first exhibit discussed below has good visibility and the second exhibit only allows a buoy to be seen when the vessel is near the buoy along-track.

Exhibit 11, Good Visibility. The cross-track contours remain somewhat stable after 2 miles. There is a correlation between improved cross-track position and passing a buoy. This is due to distance estimation to the buoy in the region 100 feet from the edge. Other less noticeable direction changes are taking place between buoys due to estimating cross-track position from the apparent slope of buoys ahead. The magnitude of the 98 percent direction of motion contour is larger for negative angles. This results from perceiving an error in cross-track position at a larger cross-track position from the desired track when the vessels have cross-track error toward the center of the channel. The correction angles to return to the desired track are large. The risk associated with traveling 100 feet from the edge of the channel is high. More than 40 percent of the vessels maintain pilot decision times of less than 15 minutes. This is due to the vessels traveling near the edge of the channel and traveling toward the channel edge when correcting from the center of the channel to the desired track.

Exhibit 13, Poor Visibility. The cross-track positions become a function of the number of buoys that are passed. There is improvement in the cross-track position contours when passing each buoy. This is because information concerning cross-track position is only available when passing a buoy by means of distance estimation. There is likewise a correlation between buoys and large directions of motion. These large directions of motion are due to corrections by those pilots that perceived their cross-track position to be in error and are returning to the ideal track. The risk associated with the poor visibility case is very high. The pilot decision times less than 15 minutes are low until the vessels pass the first buoy because all vessels are started with direction of motion away from the near edge. Upon passing the first buoy, 3000 feet, the high risk shown at 4500 feet is due to the large number of vessels now moving toward the nearest edge of the channel. About 50 percent of the vessels have pilot decision times of less than 15 minutes for the remainder of the track.

II.C.4 Ship Type Comparisons

The two ships used for comparisons are an 80,000 DWT tanker and a 250,000 DWT tanker. The difference in the two ships is reflected only in their grounding domains. The 250,000 DWT tanker requires more room for correcting errors in its direction of motion. The current run and observe model does not consider actual ship motion—this will be included in subsequent refinements of the model. Therefore, only the risk measure of pilot decision times shown in Exhibit 1 for an 80,000 DWT tanker and in Exhibit 17 for the 250,000 DWT tanker are discussed. The frequency of pilot decision times of less than 15 minutes is slightly higher for the 250,000 DWT tanker when traveling the middle of a straight channel. This difference is expected to become much greater when the ship's motion is incorporated into the straight channel run and observe model.

II.C.5 Reference Point Comparison

The two cases below have similar σ values along the selected desired tracks. The differences between the two cases is that gated buoys have two reference points. The first reference point to the left of the desired track is at the center of the channel when the observable is the matching of the visual angles formed by the gated buoys ahead. The second reference point is to the right of the desired track at the edge of the channel where ranging occurs on the buoys. The observable is the slope of the line connecting the buoys on the edge. These two reference points make the task of determining cross-track position psychologically easier when the vessel approaches the center of the channel and when the vessel gets near to the edge of the channel. There is no reference point for the LORAN-C case; the errors remain the same over the entire channel.

Exhibit 3, Reference Point. The cross-track contours reach steady-state at about 2 miles. There is no apparent correlation between passing a buoy and improved cross-track position. This is due

to modeling visual angle comparison at distances greater than 200 feet from the edge of the channel. The magnitude of the 98 percent cross-track contour reaches ± 100 feet. Large magnitudes for direction of motion contours are due to pilots having fairly large cross-track errors before perceiving their location to be incorrect. The frequency of pilot decision times less than 15 minutes is maintained at about 10 percent.

Exhibit 16, No Reference Point. The LORAN cross-track contours reach about ± 150 feet for the 98 percent contour. The additional 50 feet on each side is due to not having a nearby psychological reference point. In other words, the pilot's perception of cross-track position does not improve when the vessel moves either to the left or to the right of the desired track. The large magnitude for the 98 percent direction of motion contours is due to the pilots having locations far from the desired track when they perceive their location to be incorrect. The frequency of pilot decision times less than 15 minutes is maintained at about 10 percent (the desired track is center of channel).

At locations near the reference points, the gated buoy system provides more accurate information than does LORAN-C. The reference points occur at the center and the edge of the channel. Thus the improved information is provided where most needed to prevent grounding and to prevent crossing into the wrong side of the channel.

The risk measures of pilot decision time cannot be compared because the desired tracks are different.

TABLE II-1. DEFINITION OF CASES

CASE	AIDS TO NAVIGATION	MARINER'S DESIRED TRACK	COMMENTS
1. Gated buoys	Gated buoys, 1 n. mi. separation	Center of Channel	-
2. Gated buoys	Same as above	Center of Channel	Indifference zone = 1 ft.
3. Gated buoys	Same as above	300 feet from left edge	
4. Buoys one side	Buoys one side 1 n. mi. separation	Center of Channel	
5. Buoys one side	Same as above	200 feet from edge marked with buoys	
6. Range	Range only	On-Range	All range cases run with 1 n. mi. between range marks.
7. Range	Range only	On-Range	Indifference zone = 1 foot.
8. Range	Range only	200 ft. off-range	
9. Range	Range plus buoys one side	On-Range	
10. Range	Same as above	200 ft. off-range	Same as above.
11. Buoys one side	Buoys one side 1 n. mi. separation.	100 ft. from edge marked with buoys.	
12. Buoys one side	Same as above	Same as above	Indifference zone = 1 foot.
13. Buoys one side	Same as above	Same as above	Poor visibility case: Information provided only when buoy is abeam.
14. Buoys one side	Same as above	Same as above	Poor visibility case. Indifference zone = 1 foot.
15. Radar PPI scope	Radar fixing on buoys on one side	Center of Channel	Radar uses information only from buoys on channel edge.
16. Loran - C	Loran - C	Center of Channel	σ reflects only short-term variable errors.
17. Gated buoys	1 n. mi. separation	Center of Channel	250,000 DWT Vessel

Initial Conditions: P distribution between ± 50 ft. of ideal track. ψ distributed between .2 and 3.4 degrees. Indifference zones are 25 ft. except where indicated. Vessels used are 80,000 DWT except where indicated.

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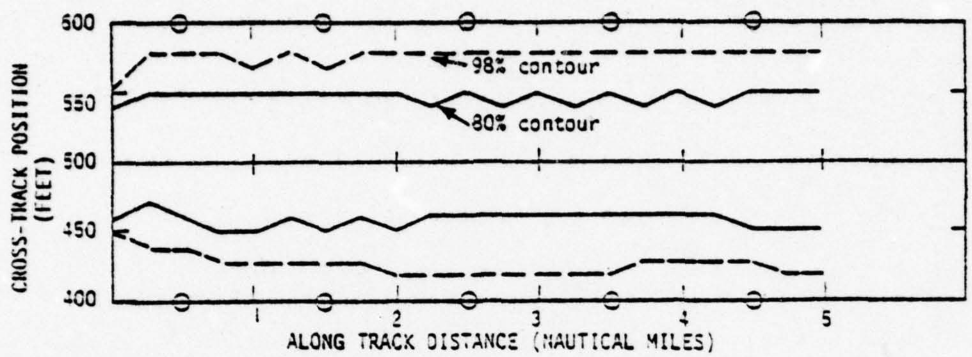
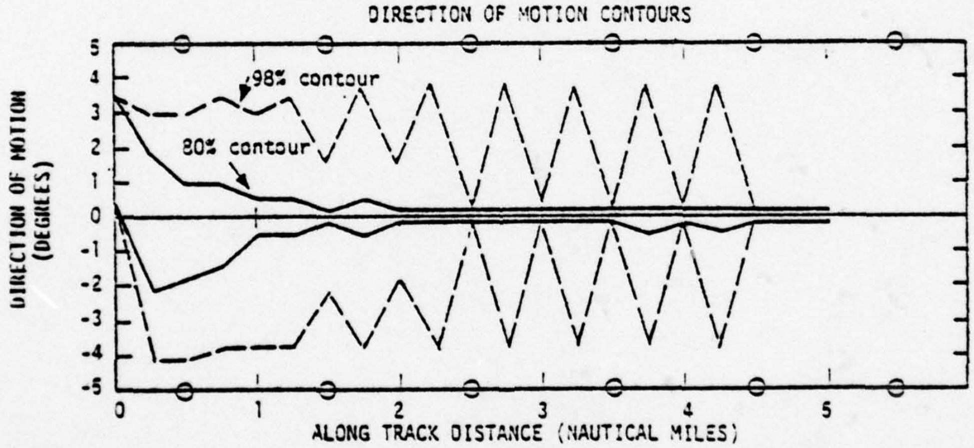
Exhibit 1: Gated Buoys/Center of Channel

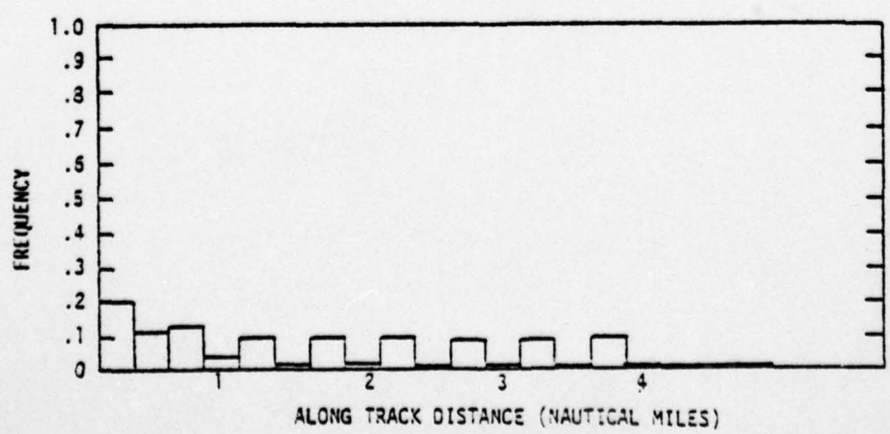
CROSS-TRACK POSITION CONTOURS



DIRECTION OF MOTION CONTOURS



FREQUENCY OF PILOT DECISION TIMES LESS THAN OR EQUAL TO 15 MINUTES



(88)

Exhibit 2: Gated Buoys/Center of Channel
(Indifference Zone = 1 FOOT)

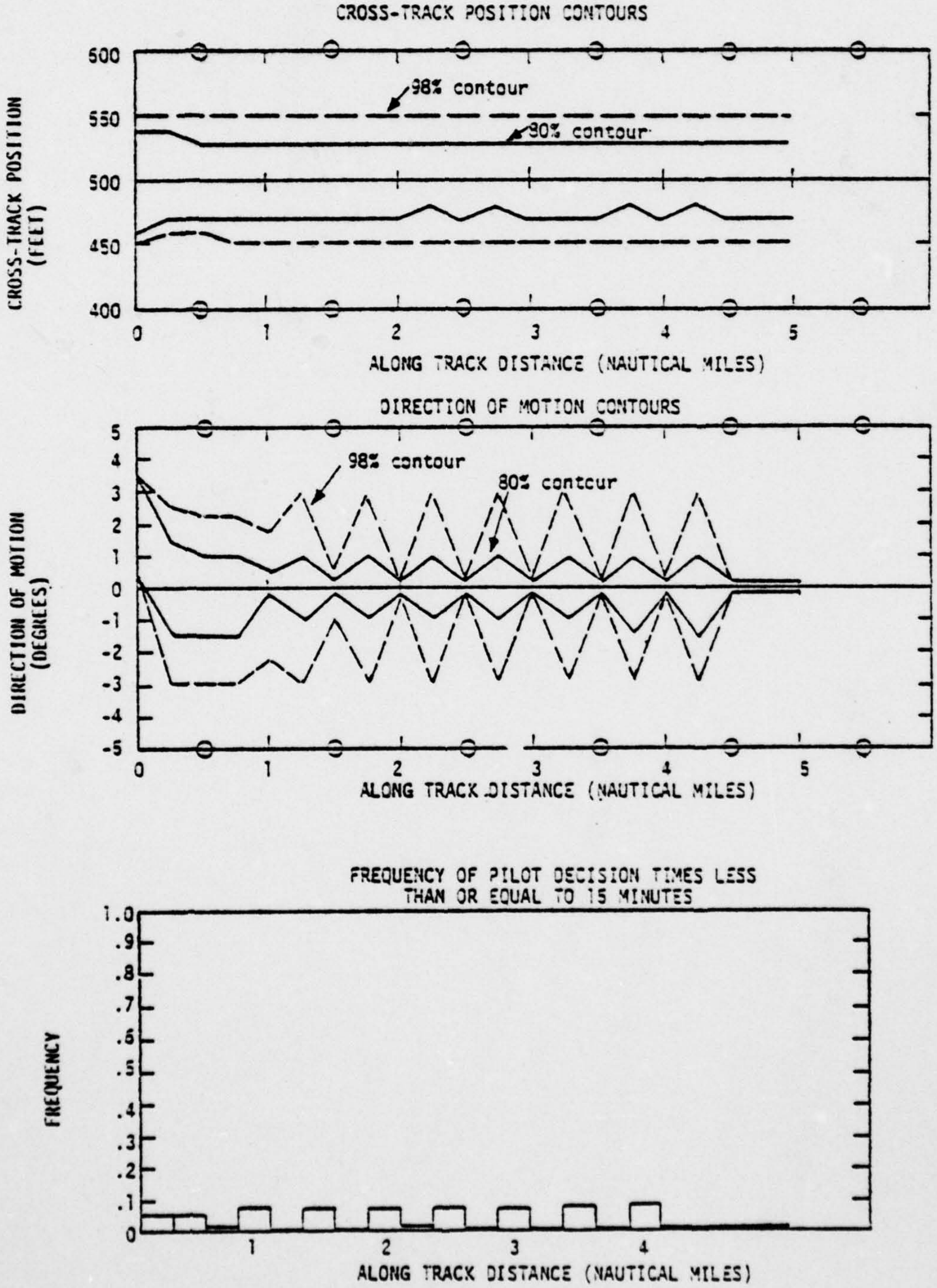


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Exhibit 3: Gated Buoys/300 FT from Edge

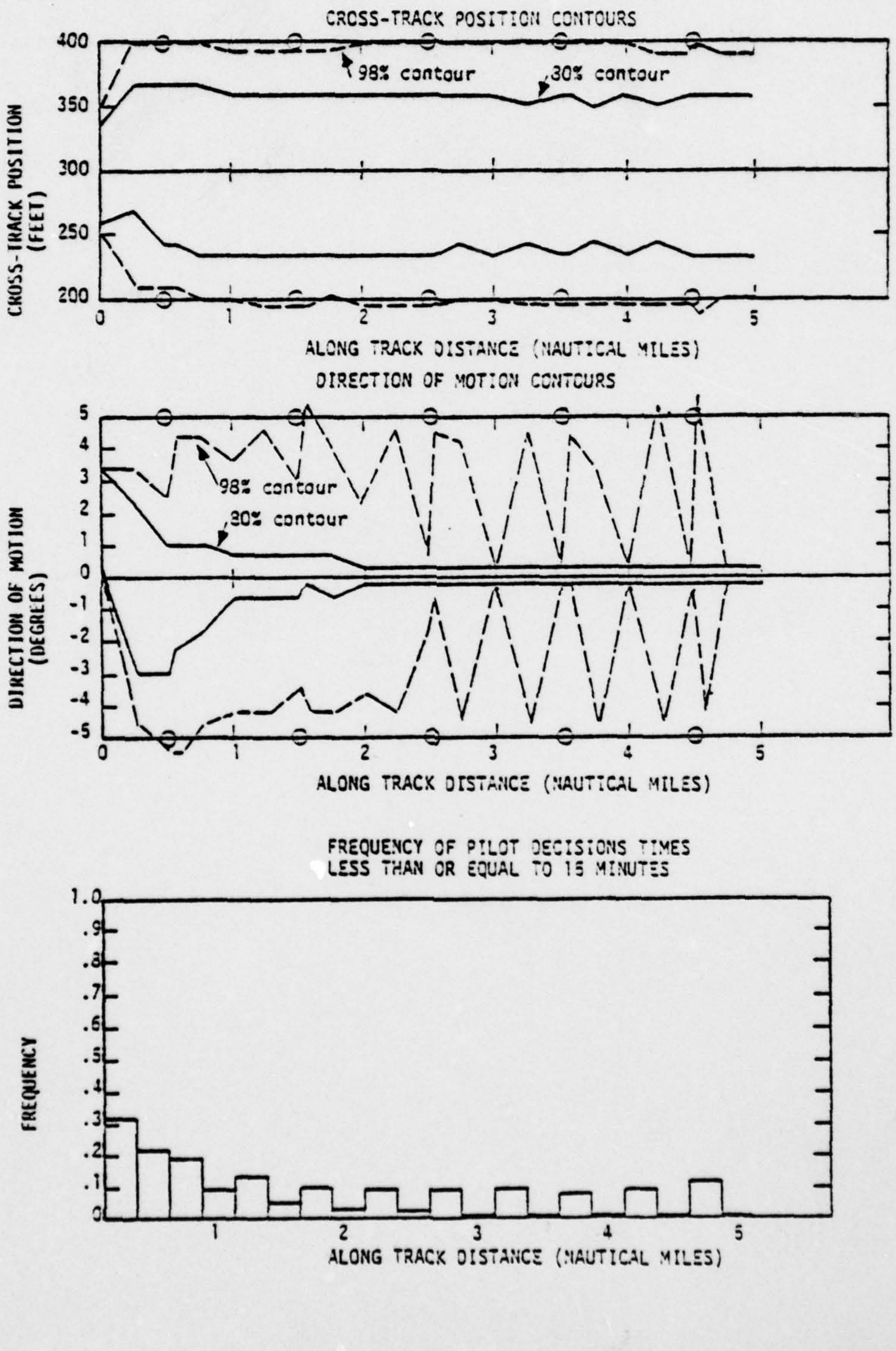
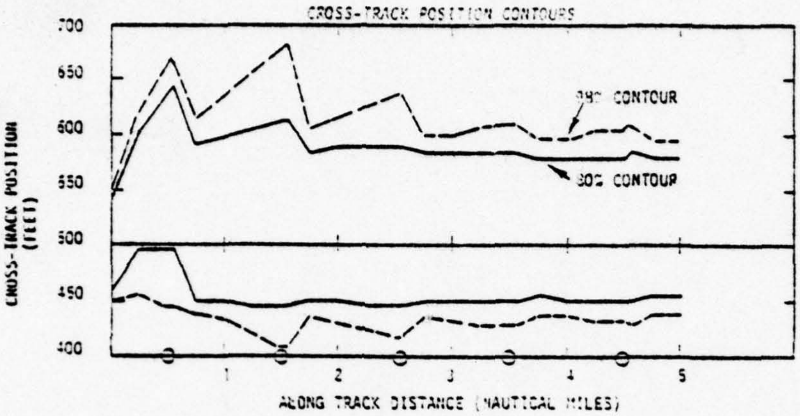
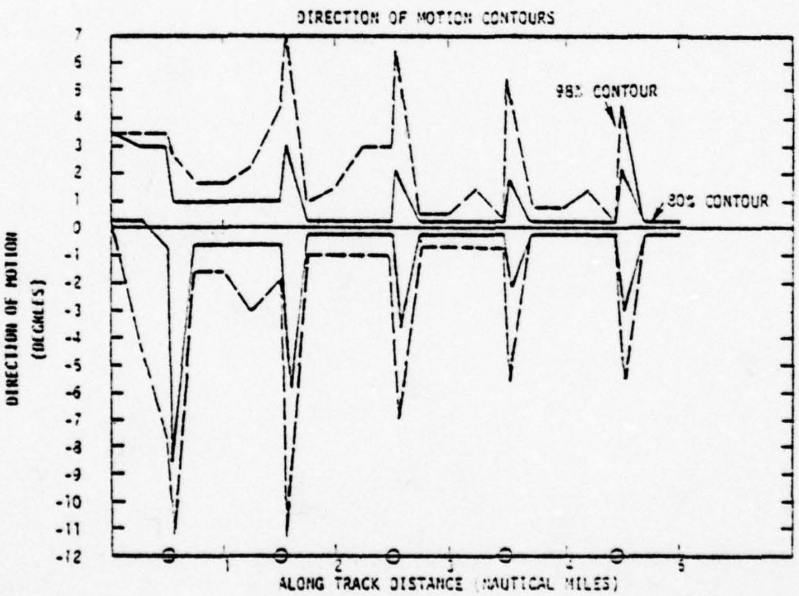


Exhibit 4: Buoys One Side/Center of Channel





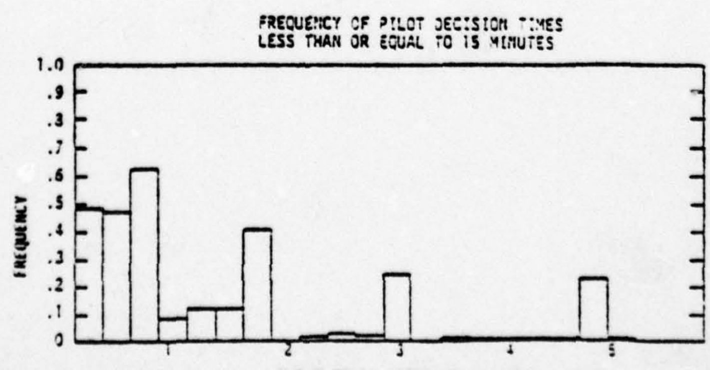


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Exhibit 5: Buoys One Side/200 FT from Edge

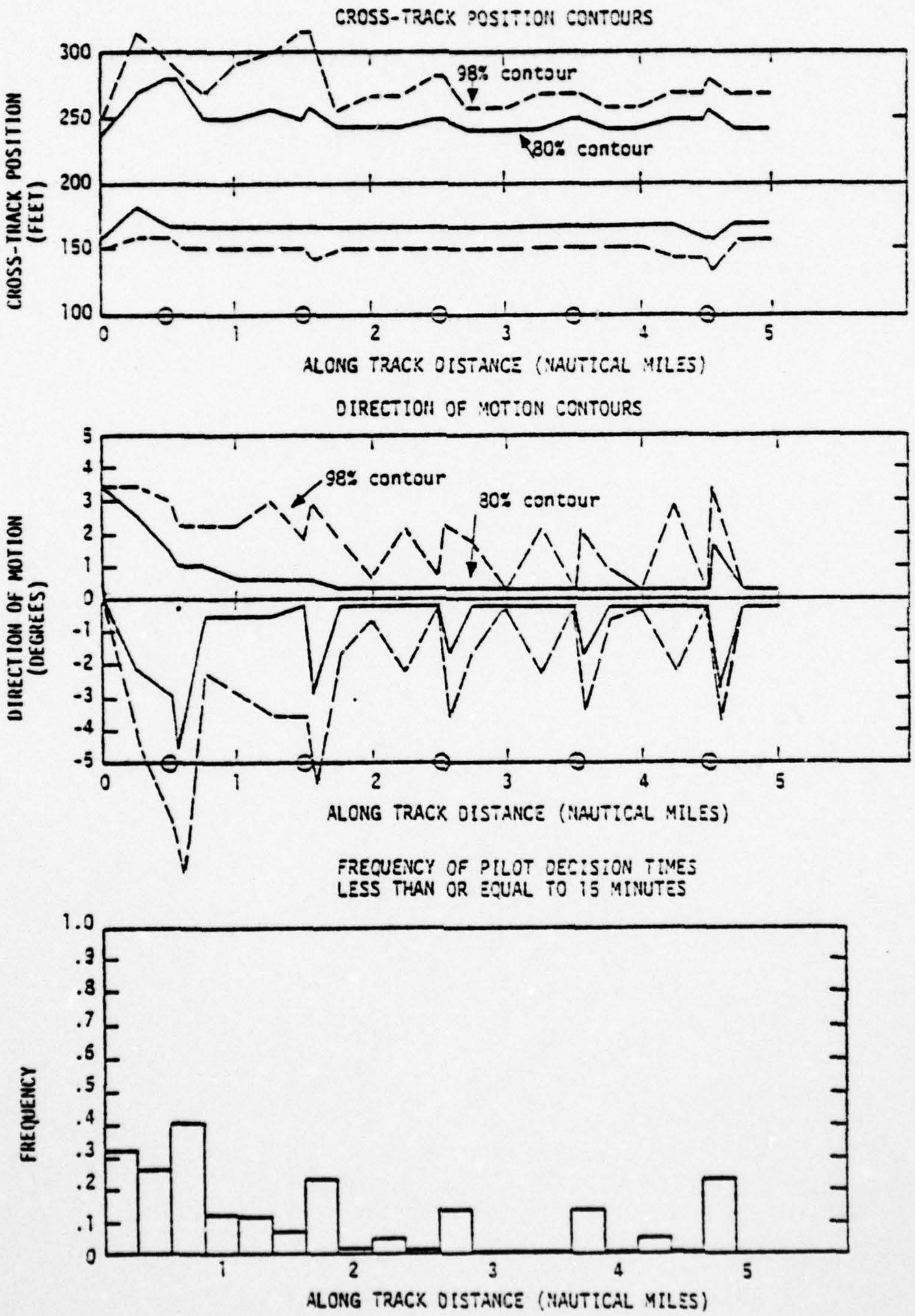

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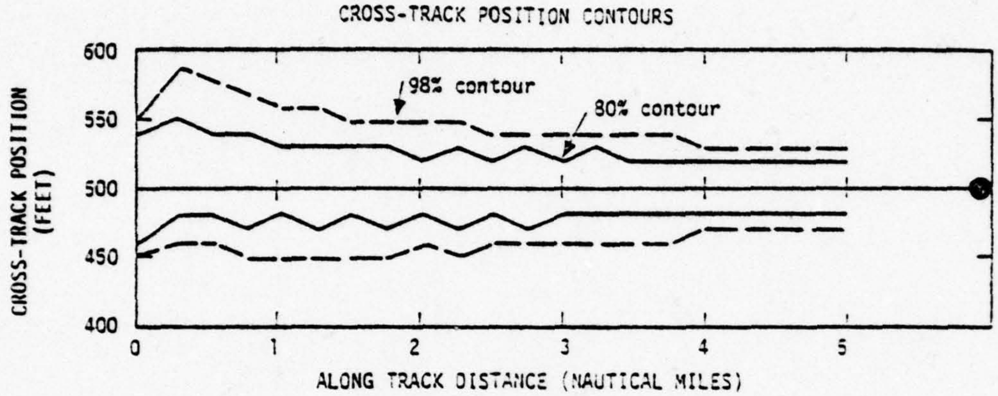
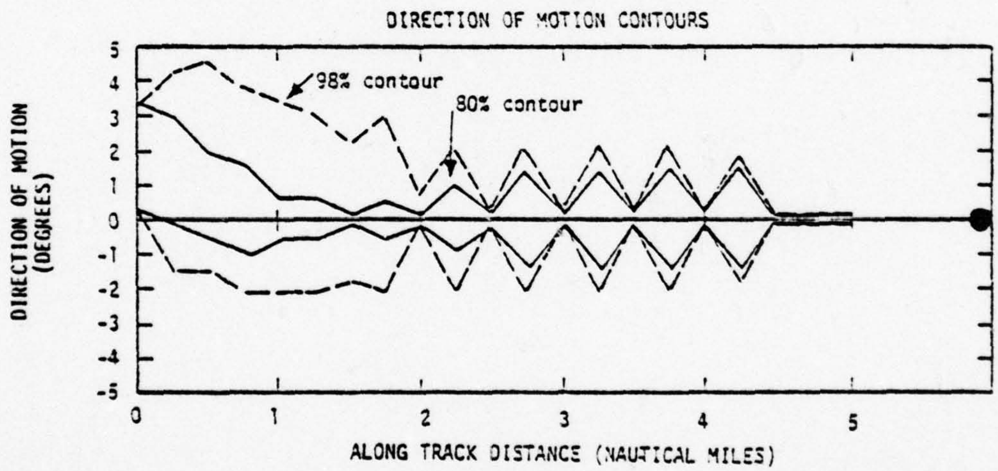
Exhibit 6: Range/Center of Channel





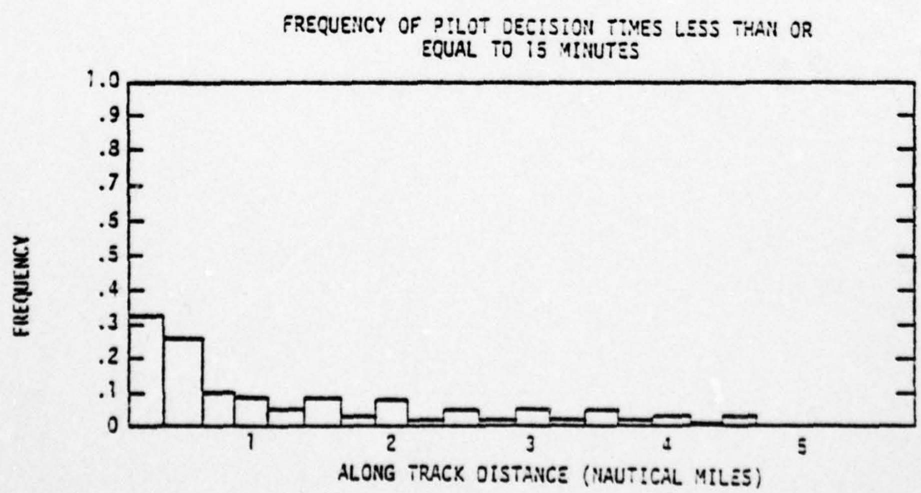


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Exhibit 7: Range/Center of Channel
(Indifference Zone = 1 FOOT)

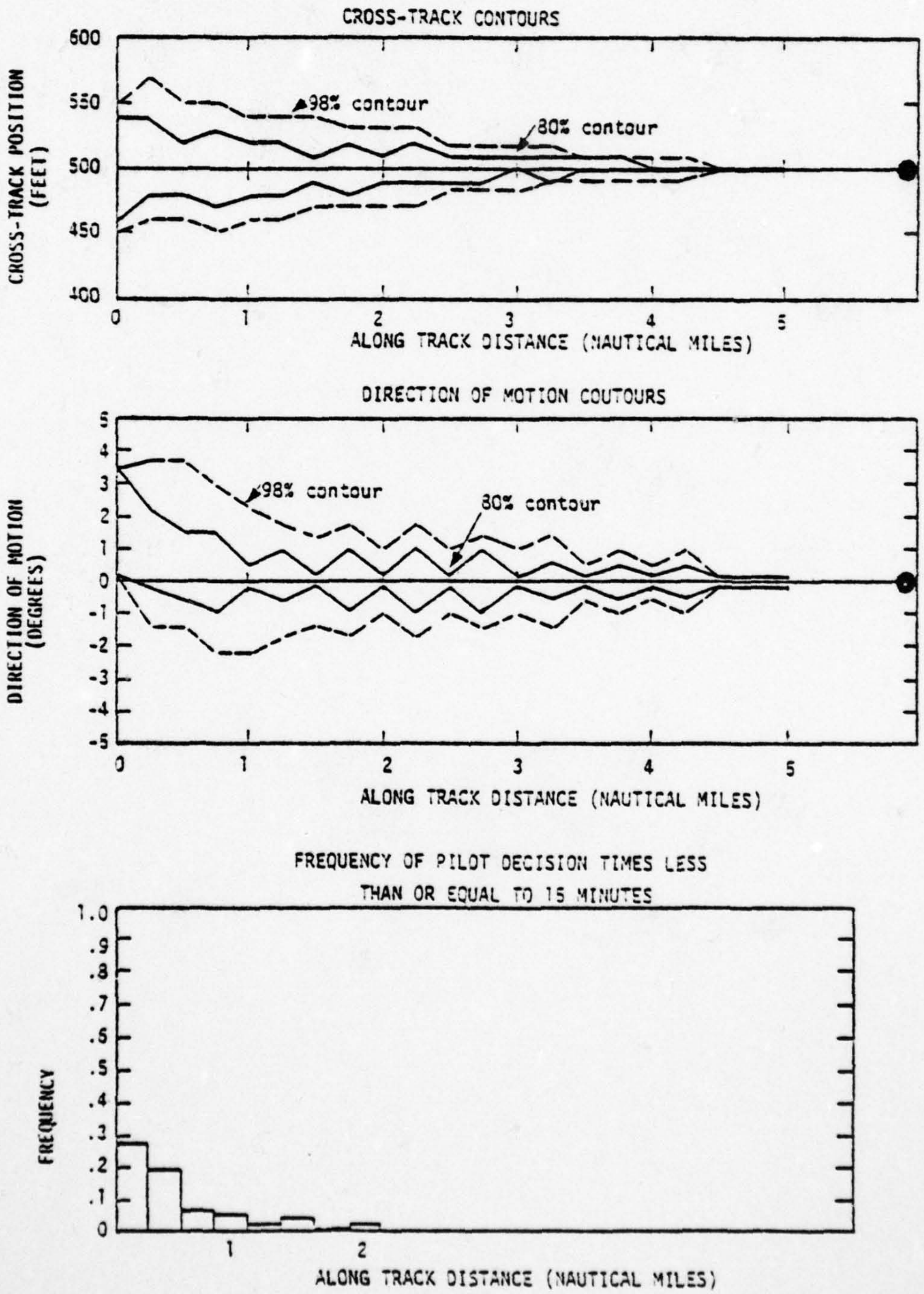

Exhibit 8: Range/300 FT from Edge

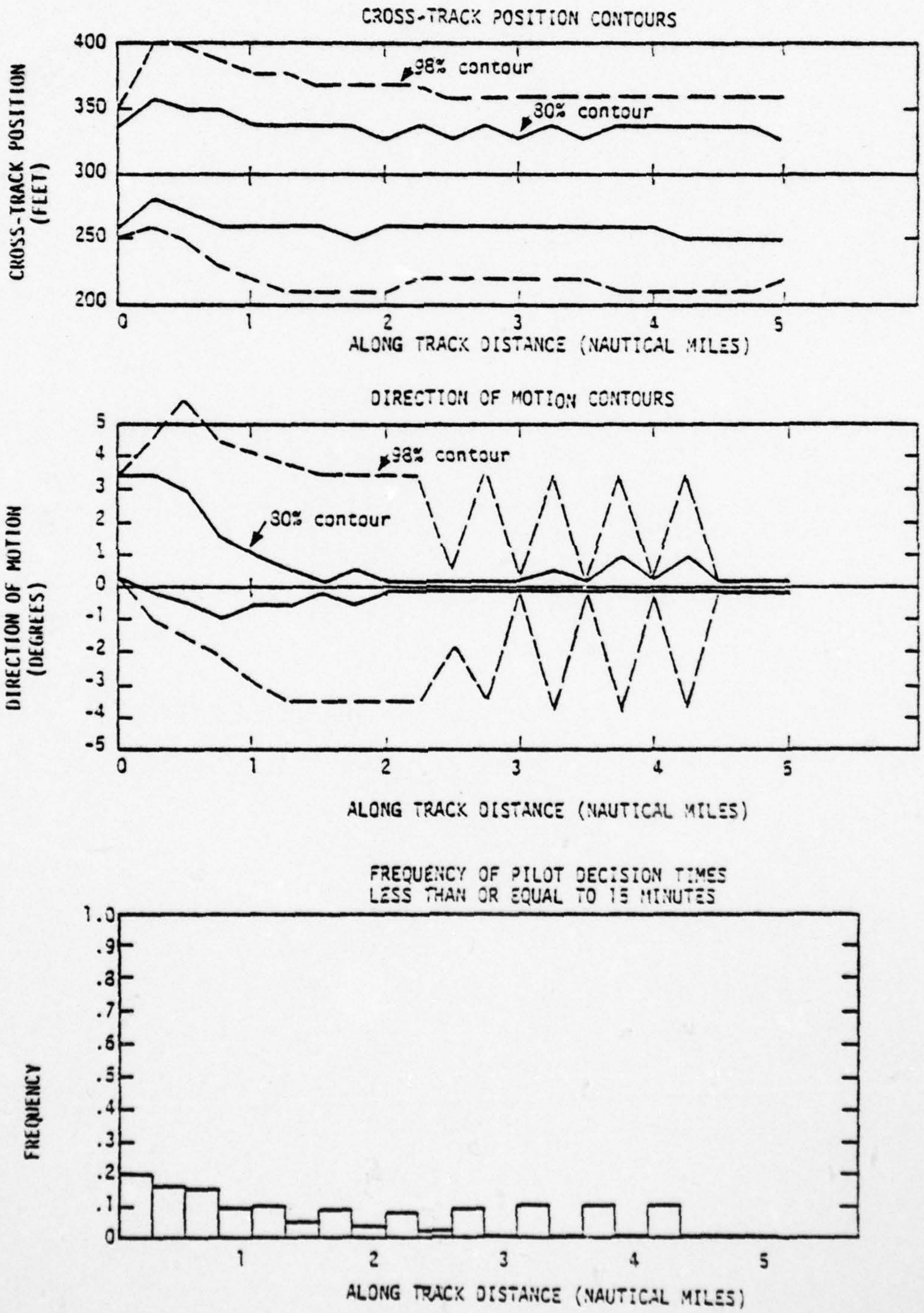

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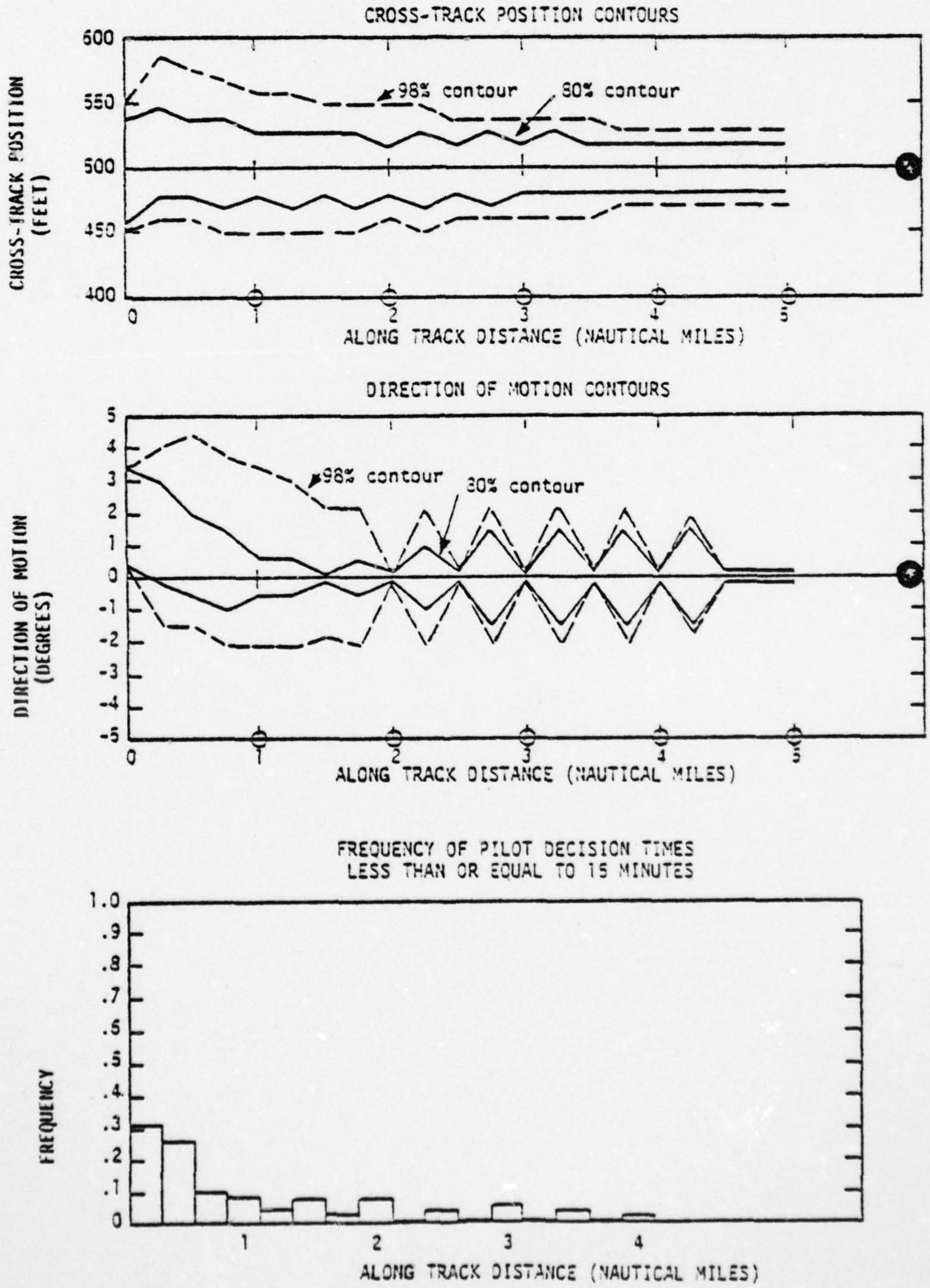
Exhibit 9: Range with Buoys/Center of Channel



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STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS-PHASE I.--ETC(U)

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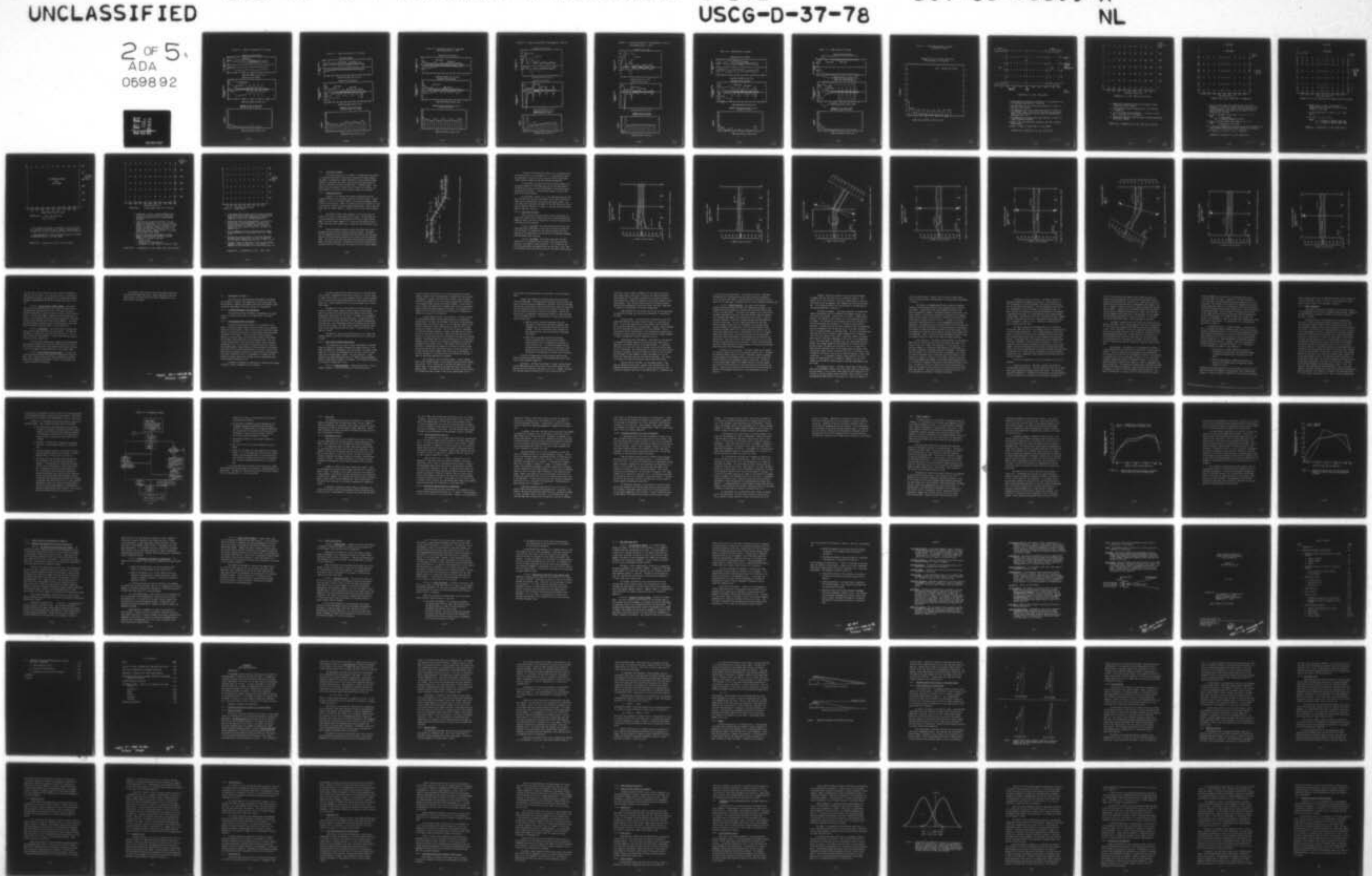

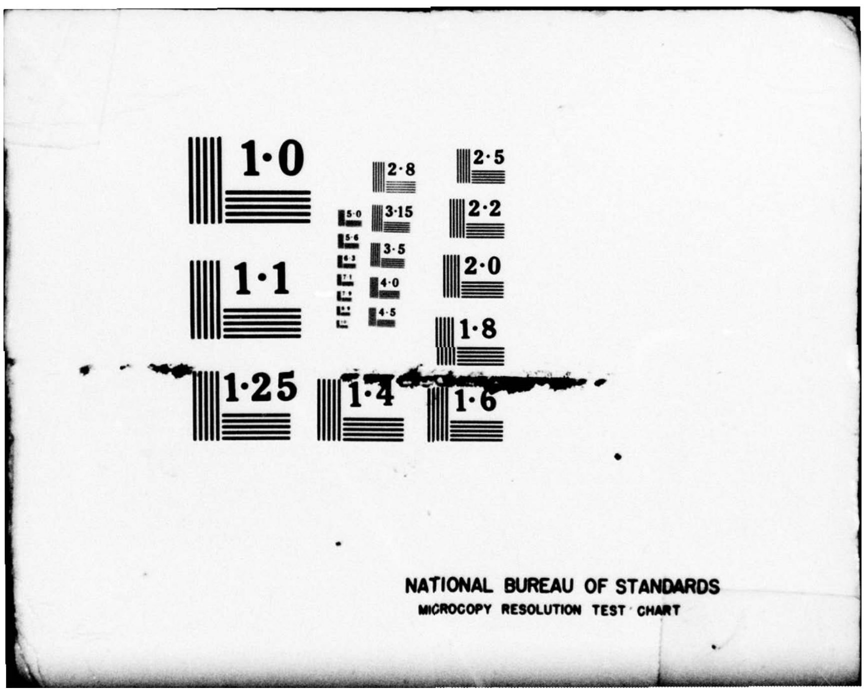
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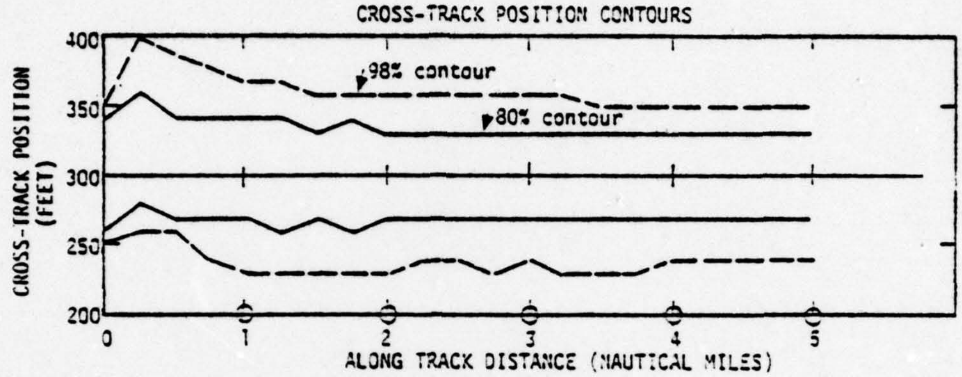
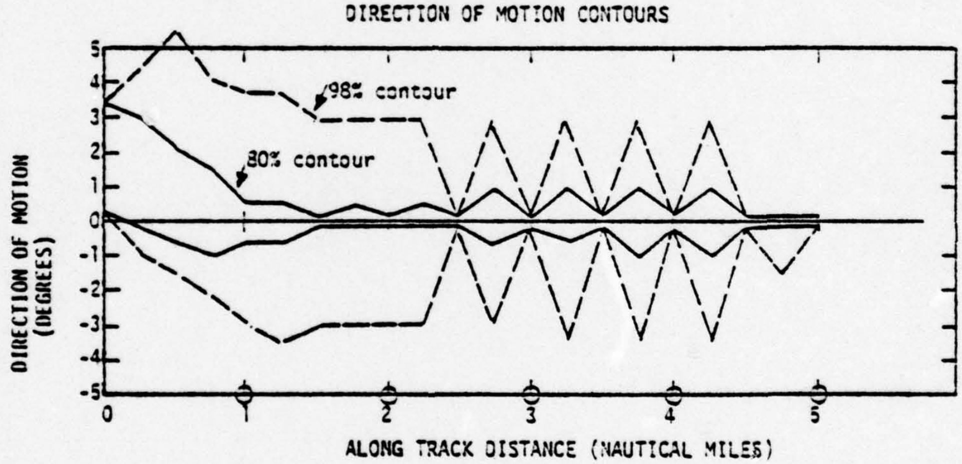
NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

Exhibit 10: Range with Buoys/300 FT from Edge

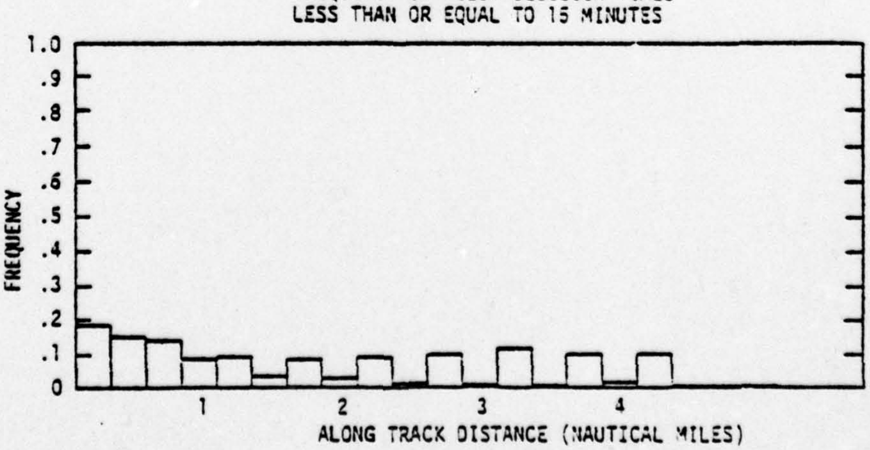
CROSS-TRACK POSITION CONTOURS



DIRECTION OF MOTION CONTOURS

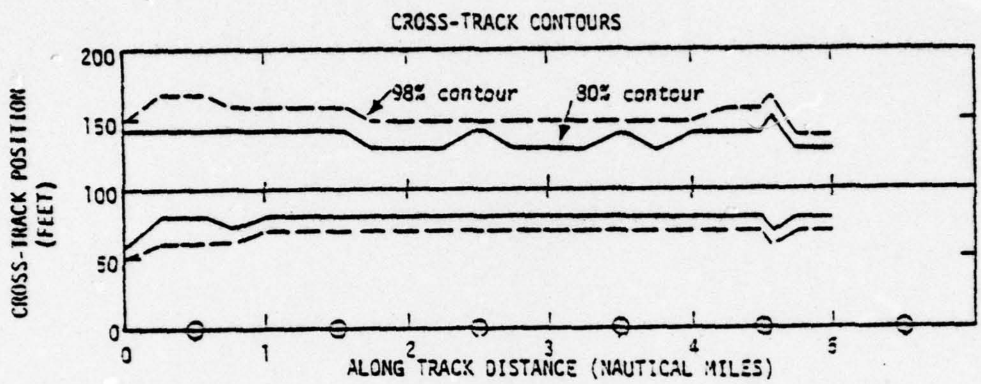


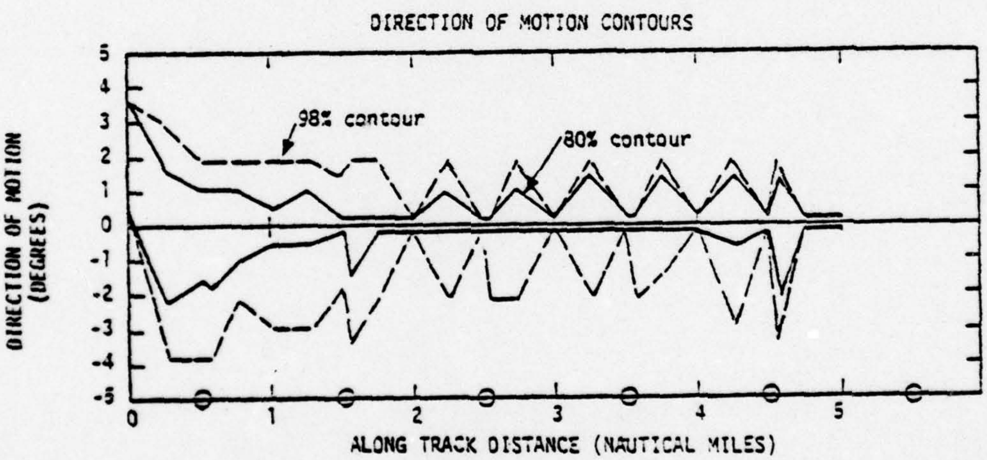
FREQUENCY OF PILOT DECISION TIMES
LESS THAN OR EQUAL TO 15 MINUTES

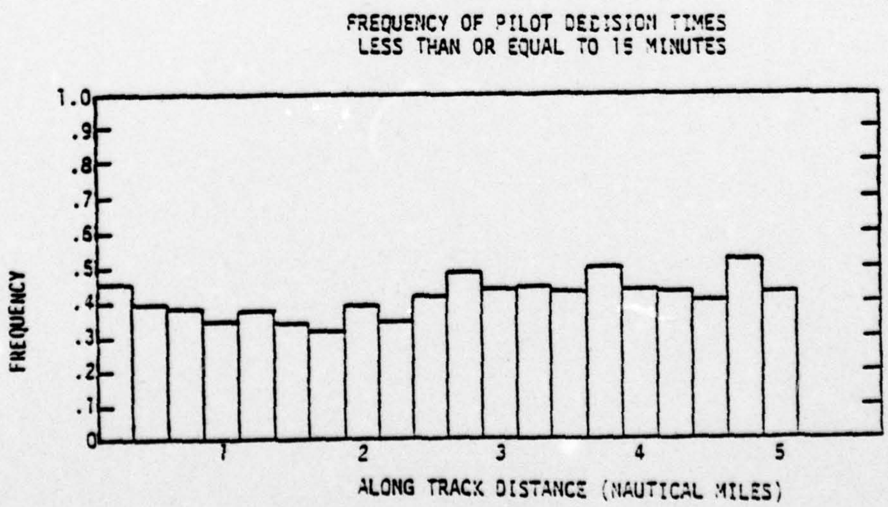


97

Exhibit 11: Buoys One Side/100 FT from Edge

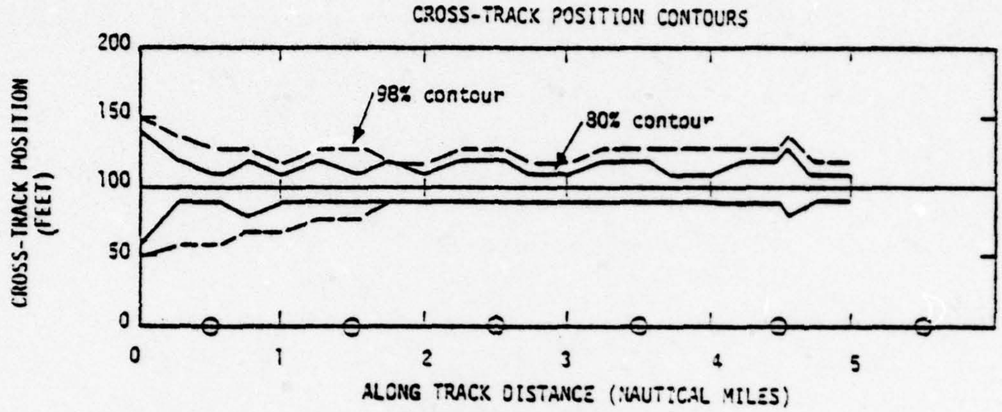


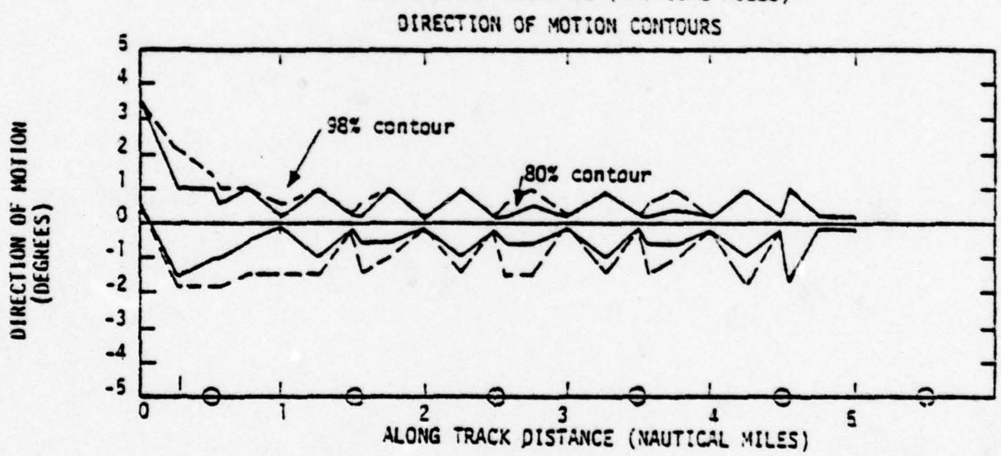


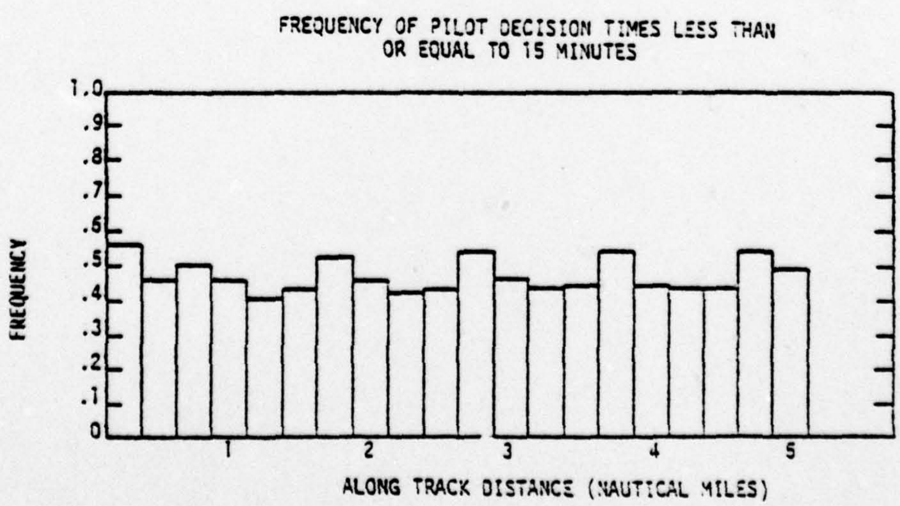


98

Exhibit 12: Buoys One Side/100 FT from Edge
(Indifference Zone = 1 FOOT)

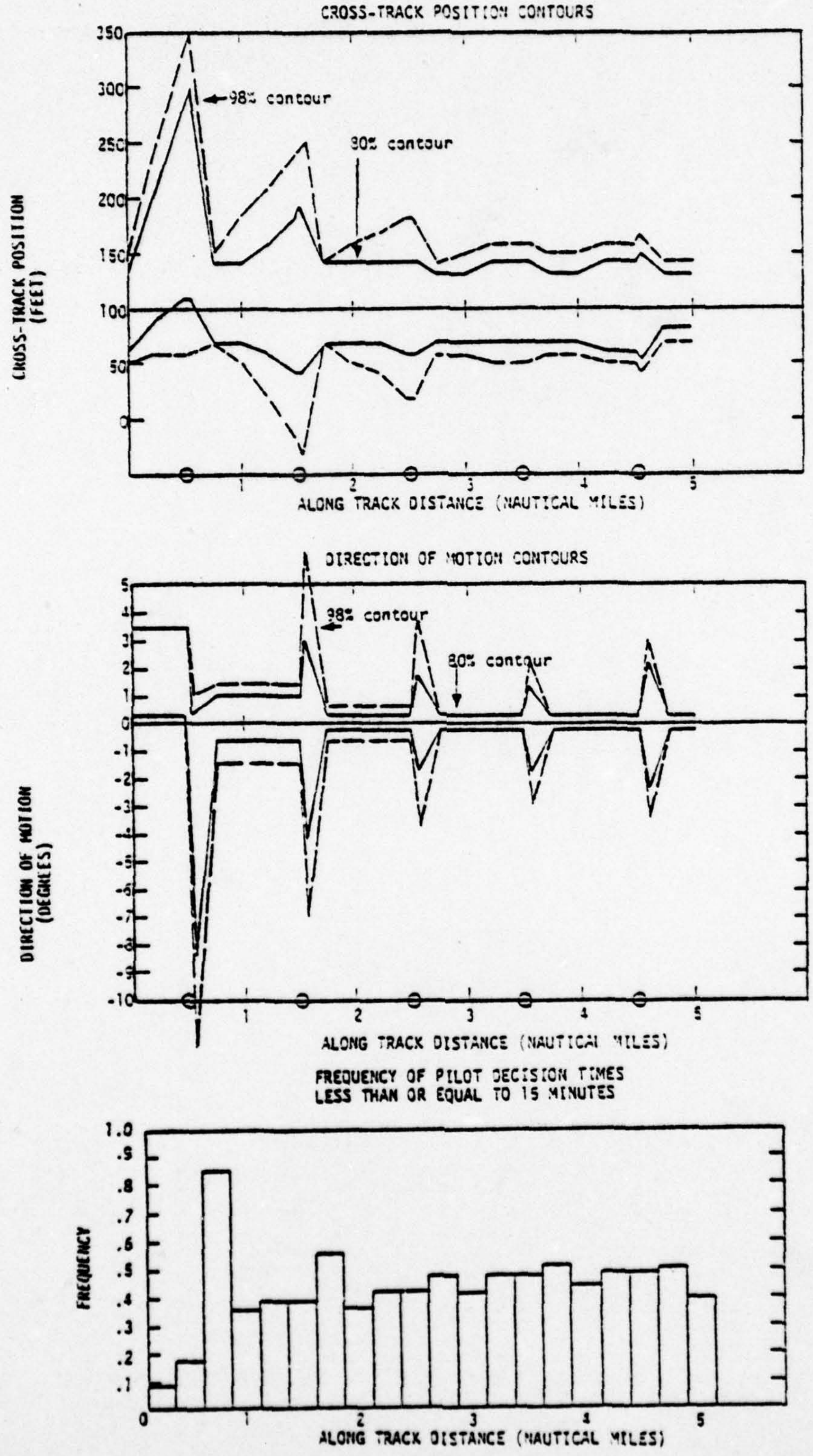






99

Exhibit 13: Buoys One Side/100 FT from Edge/Poor Visibility



100

Exhibit 14: Buoys One Side/100 FT from Edge/Poor Visibility
(Indifference Zone = 1 Foot)

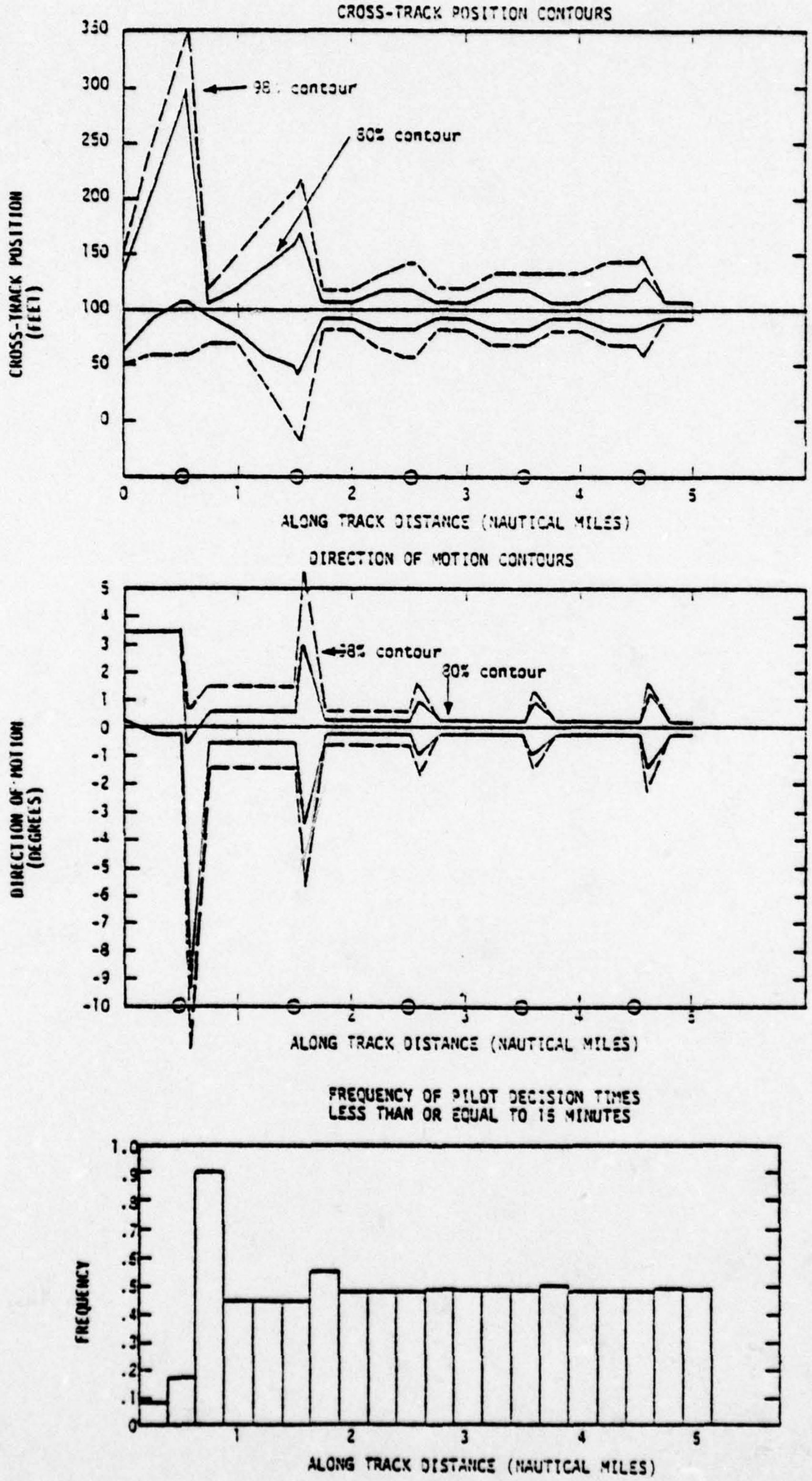
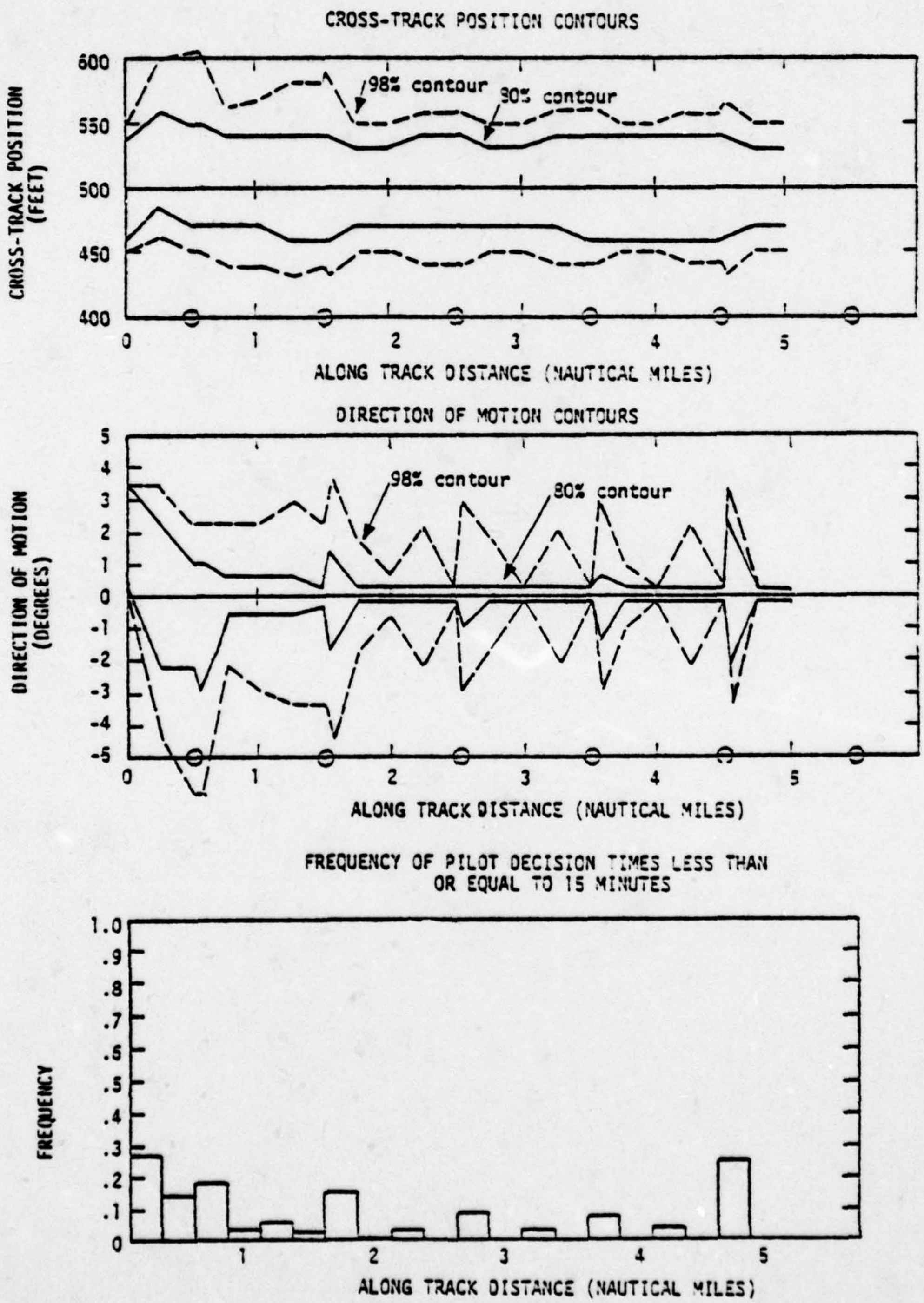


Exhibit 15: Radar/Center of Channel



102

Exhibit 16: LORAN-C/Center of Channel

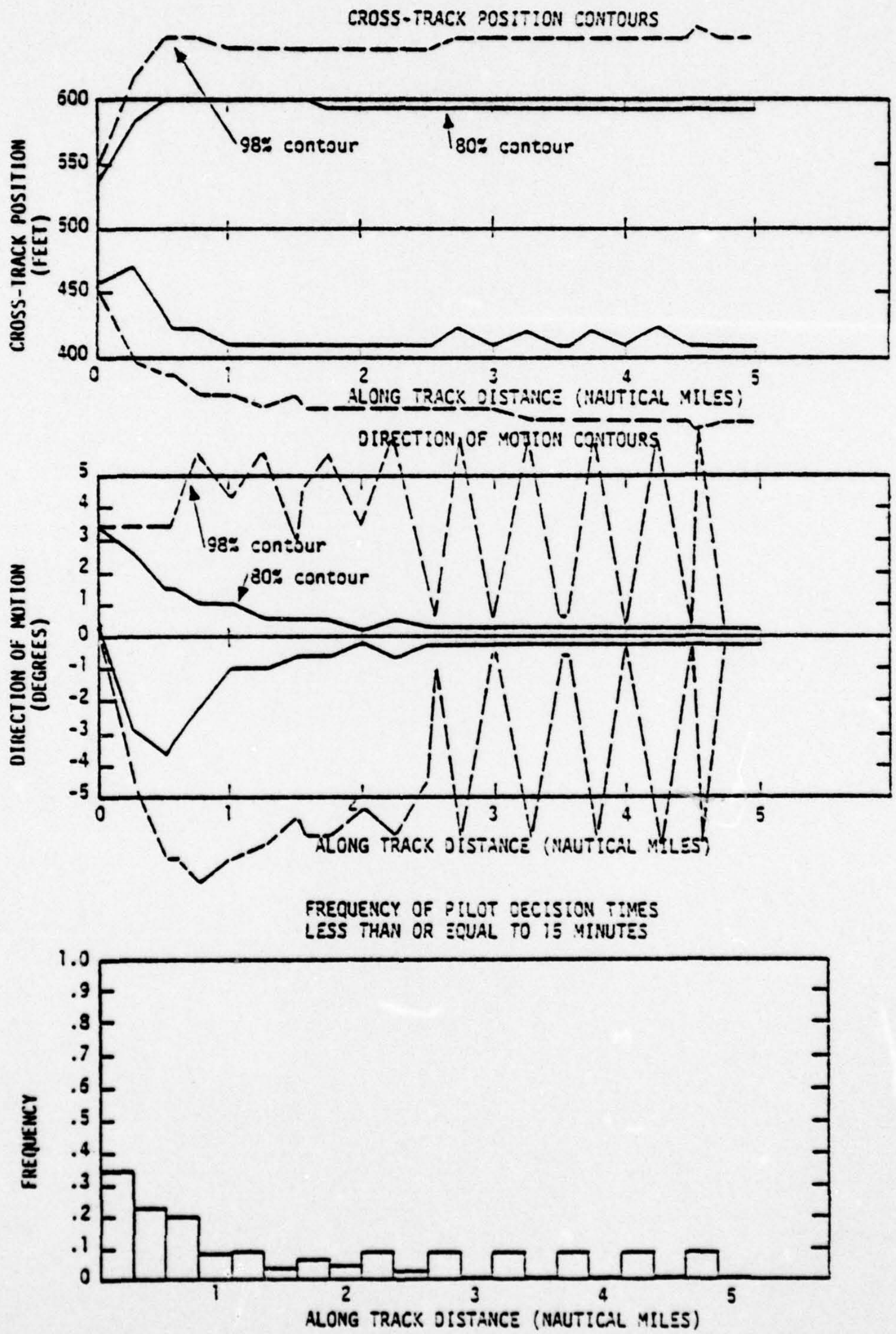
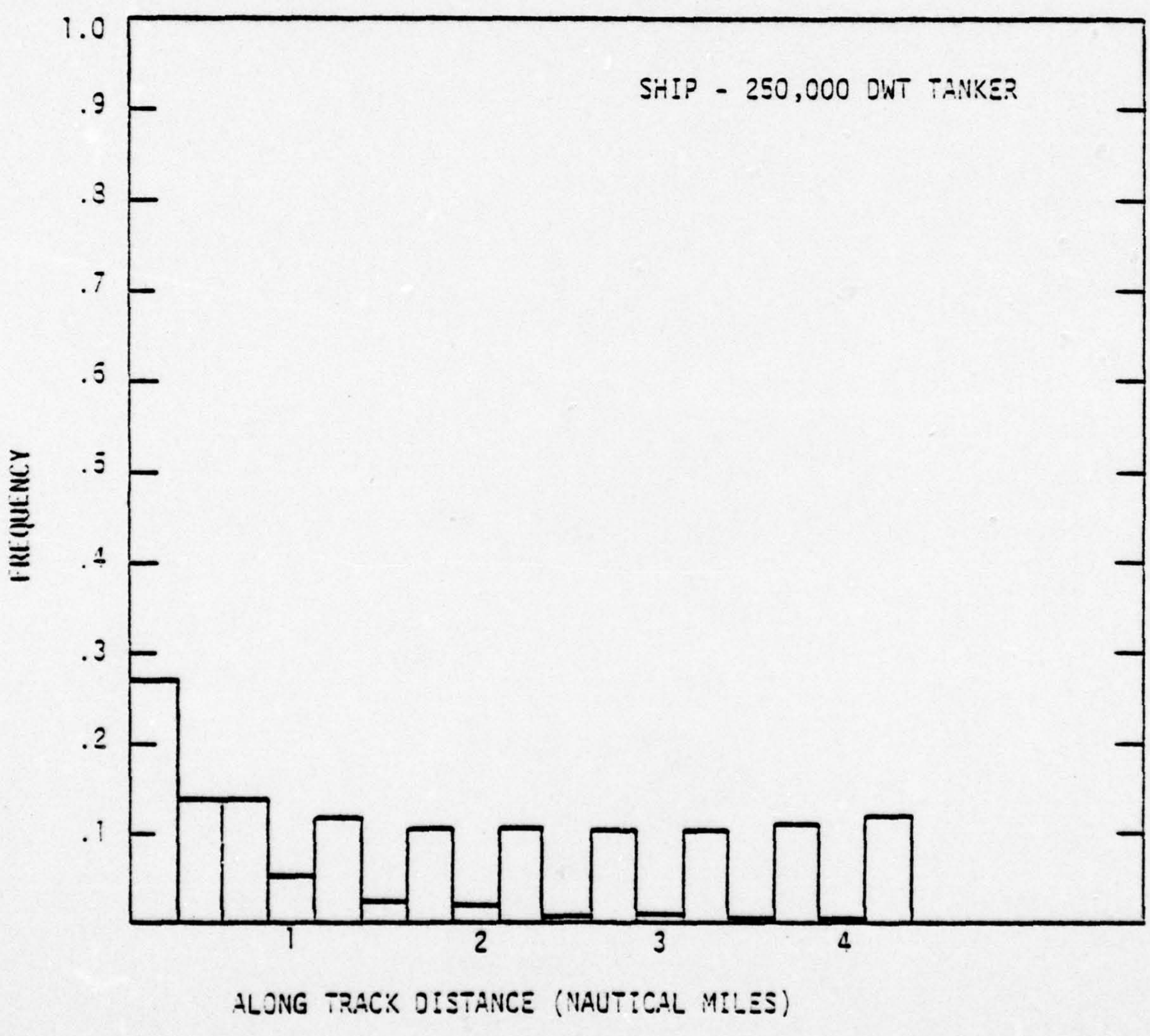


Exhibit 17: Gated Buoys/Center of Channel
250,000 DWT tanker

FREQUENCY OF PILOT DECISION TIMES LESS
THAN OR EQUAL TO 15 MINUTES



104

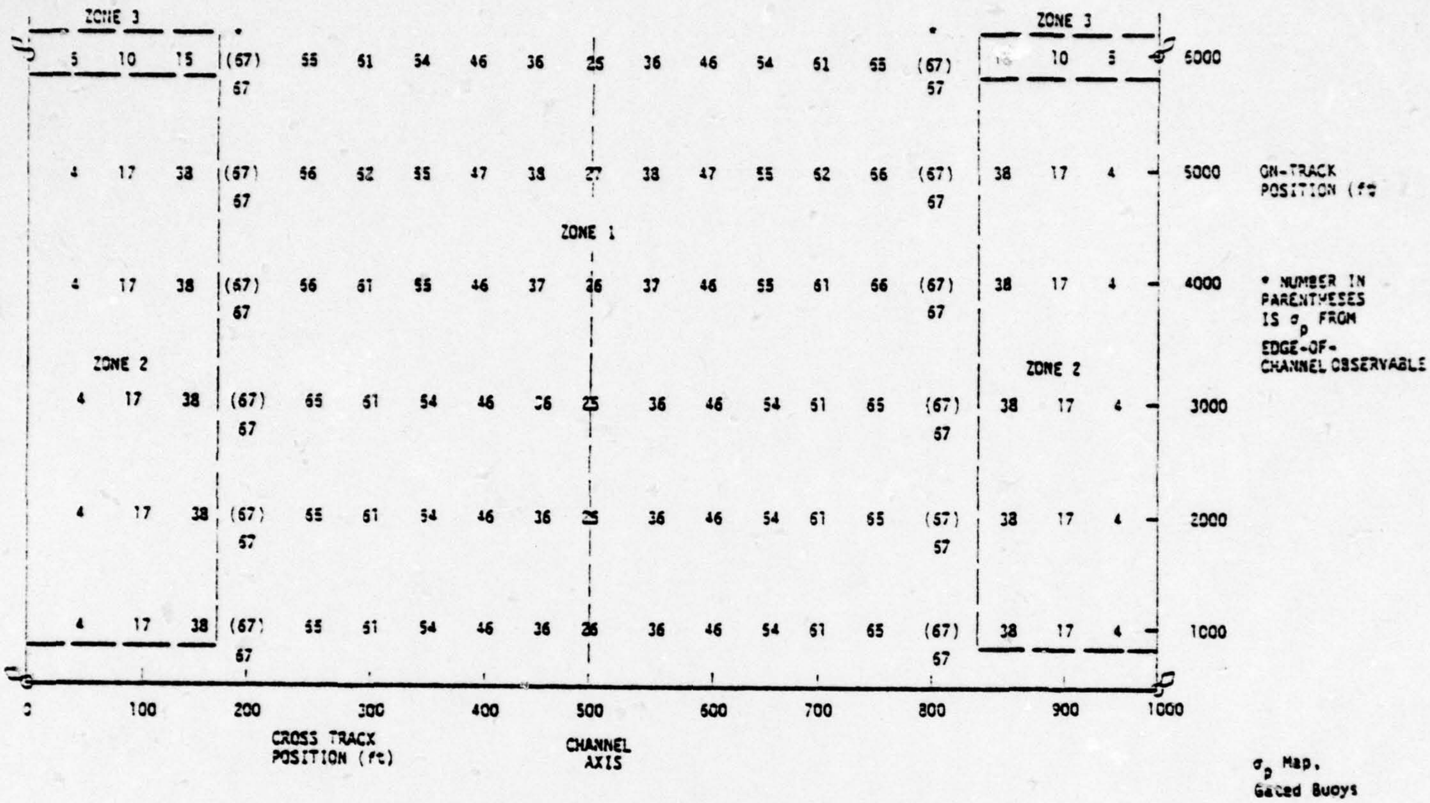


FIGURE B-20.a σ_p MAP, GATED BUOYS.

- Three zones are displayed corresponding to the observable for fixing cross-track position in the zone.
- The observable for fixing cross-track position in Zone 1 is matching visual angles.
- The observable for fixing cross-track position in Zone 2 is the apparent slope of the line of buoys marking the channel edge. Fixing cross-track position using this observable is discussed in B.I. 2.
- The observable for fixing cross-track position in Zone 3 is direct distance estimation.
- Zones 1 and 2 are arbitrarily meshed at 200 feet from each channel edge.
- Zone 3 is used only when there is a buoy abeam.

FIGURE B-20.b DISCUSSION OF σ_p MAP, GATED BUOYS.

95

105

ON TRACK POSITION (FT.)	100	200	300	400	500	600	700	800	900
6000	10	20	30	40	50	60	70	80	90
5000	17	67	150	267	417	600	817	1067	1350
4000	17	67	150	267	417	600	817	1067	1350
3000	17	67	150	267	417	600	817	1067	1350
2000	17	67	150	267	417	600	817	1067	1350
1000	17	67	150	267	417	600	817	1067	1350
0	10	20	30	40	50	60	70	80	90

CROSS-TRACK POSITION (FT.)

FIGURE B-21.a σ_p MAP, BUOYS LEFT SIDE ONLY.

- Observable is apparent slope of line formed by bouys lining left side of channel.
- Error equation relating observable and P are reported in Appendix B.
- σ_p's are height-of-eye dependent. A height of eye of 60 ft. was used for this example.
- Cross-track position fixed by direct distance estimation when buoy is abeam.

FIGURE B-21.b DISCUSSION OF σ_p MAP, BUOYS LEFT SIDE ONLY.

95%

106

— REAR RANGE

— FRONT RANGE

	100	200	300	400		500		600	700	800	900		NAUTICAL MILES
92	73	55	37	19	10	2	10	19	37	55	73	92	1
100	81	61	42	23	13	5	13	23	42	61	81	100	2
107	86	66	47	27	18	11	18	27	47	66	86	107	3
113	92	72	52	33	24	18	24	33	52	72	92	113	4
119	99	79	59	41	33	27	33	41	59	79	99	119	5
127	107	87	68	51	43	37	43	51	68	87	107	127	6

CROSS-TRACK POSITION (FT.)

ON TRACK POSITION (N. MI.)

FIGURE B-22.a σ_p MAP, RANGE CASE #1 (RANGE ONLY).

- Error in fixing cross-track position (σ_p) due to two components: (1) error in fixing cross-track position from a given horizontal visual angle, given the observer is a known distance from the range; and (2) error in fixing distance from the range.
- Error in horizontal visual angle is: $\sigma_\phi = 0.5' + 0.1\phi$ where
  ϕ = visual angle
  0.5 is constant component of error.
- Error in fixing distance from range is: $\sigma_D = 0.1\,D$.
  where D = distance to front range.
- σ_ϕ and σ_D are propagated to cross-track position to obtain σ_p's, using standard least squares error propagation techniques.
- On range σ_p's are due only to 0.5´ ambiguity.

FIGURE B-22.b DISCUSSION OF σ_p MAP, RANGE CASE #1.

95

— REAR RANGE

— FRONT RANGE

(σ_p in feet)

													NAUTICAL MILES
52	42	32	22	12	7	2	7	12	22	32	42	52	1
60	48	37	26	14	9	5	9	14	26	37	48	60	1.5
55	45	35	25	15	10	5	10	15	25	35	45	55	2
61	51	41	31	21	16	11	16	21	31	41	51	61	3
68	58	48	38	28	23	18	23	28	38	48	58	68	4
77	67	57	47	37	32	27	32	37	47	57	67	77	5
82	72	62	52	42	37	32	37	42	52	62	72	82	5.5
87	77	67	57	47	42	37	42	47	57	67	77	87	6
	100	200	300	400		500		600	700	800	900		

ON TRACK POSITION (N. MI. FROM FRONT RANGE)

CROSS TRACK POSITION (FT.)

FIGURE B-23.a σ_p MAP, RANGE CASE #2, RANGE PLUS BUOYS ONE SIDE

- Range case #2 is same as range case #1 except that buoys are used to better estimate distance to the range.
- σ_ϕ for range case #2 is same as σ_ϕ for range case #1.
- σ_D = min. $\{0.1\ d_i;\ 0.1\ d_{i-1}\}$

  where:
  d_i = distance to nearest ahead buoy.
  d_{i-1} = distance to nearest astern buoy.

FIGURE B-23.b DISCUSSION OF σ_p MAP, RANGE CASE #2

9-5-70

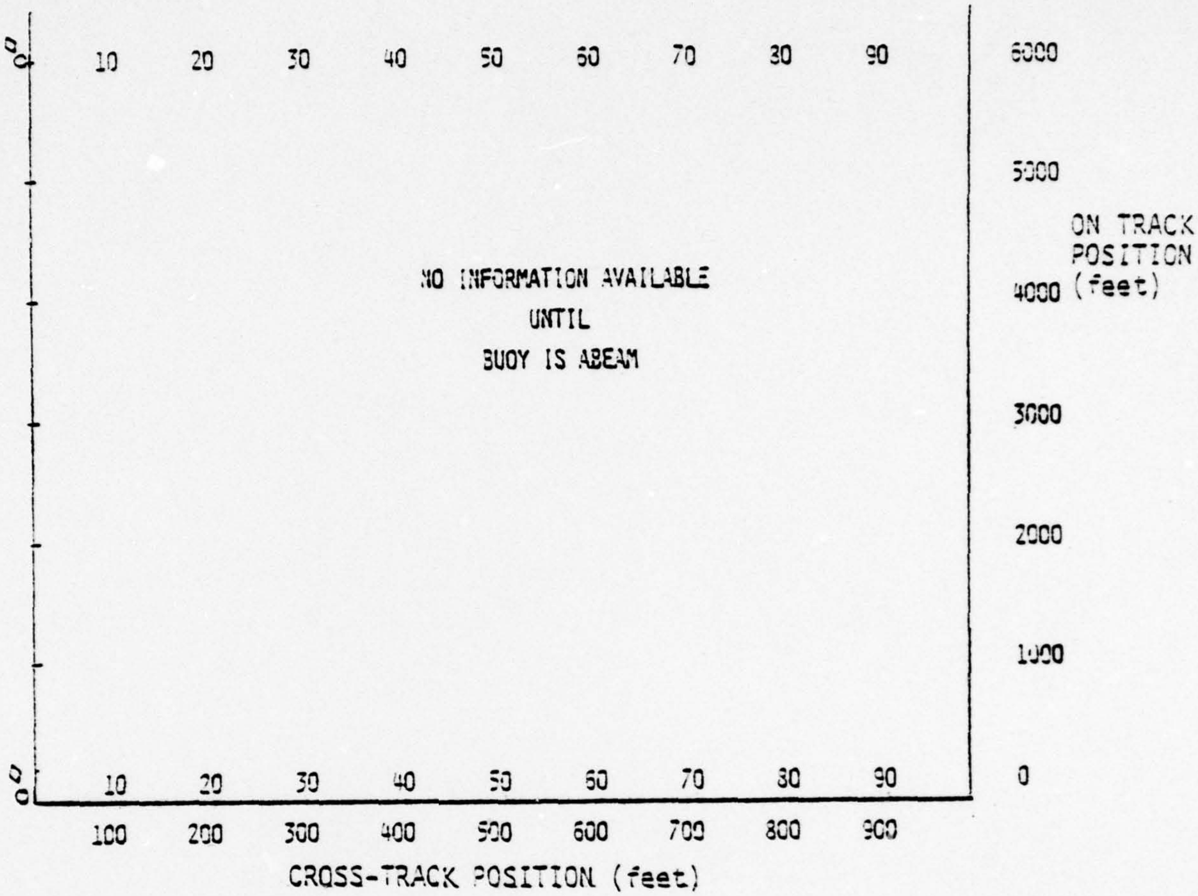


FIGURE B-24.a. σ_p Map; Buoys One Side,
Poor Visibility

- Two zones are displayed. Visibility is such that buoys are visible only when the buoy is abeam. Between buoys, no buoys are visible and the mariner has no A/N information.

- The observable for fixing cross-track position is direct distance estimation to the buoy abeam.

FIGURE B-24.b Discussion for Poor Visibility Case.

9-0/0

ON TRACK POSITION (FT)	100	200	300	400	500	600	700	800	900	1000
6000	15	16	18	18	17	17	17	17	18	18
5000	10	20	30	40	50	60	70	80	90	100
4000	10	20	30	40	50	60	70	80	90	100
3000	10	20	30	40	50	60	70	80	90	100
2000	10	20	30	40	50	60	70	80	90	100
1000	10	20	30	40	50	60	70	80	90	100
	15	16	18	18	17	17	17	17	18	18

CROSS-TRACK POSITION (FT.)

FIGURE B-25.a σ_p MAP: RADAR, BUOYS LEFT SIDE ONLY.

- Contributor to error in region between buoys is ability to align cursor on PPI scope and estimate distance to side of channel marked by buoys.
- Timing errors and bearing errors do not substantially contribute in this region, since the effects of timing errors is to lengthen or foreshorten the apparent channel displayed on the screen, and the effect of bearing error is to rotate the apparent channel marked by the buoys and displayed on the screen.
- Errors in the region where there is a buoy abeam are due to errors affecting directed estimate of distance to the buoy:
  - timing errors;
  - resolution of range read-out,
  - correction of slant range to horizontal range.

FIGURE B-25.b DISCUSSION OF σ_p MAP; RADAR, BUOYS LEFT SIDE ONLY.

95%

110

ON TRACK POSITION (feet)	100	200	300	400	500	600	700	800	900
6000	74	74	74	74	74	74	74	74	74
5000	74	74	74	74	74	74	74	74	74
4000	74	74	74	74	74	74	74	74	74
3000	74	74	74	74	74	74	74	74	74
2000	74	74	74	74	74	74	74	74	74
1000	74	74	74	74	74	74	74	74	74
0	74	74	74	74	74	74	74	74	74

CROSS-TRACK POSITION (feet)

FIGURE B-26.a σ_p MAP: LORAN-C

- It was assumed that the mariners would not transit the waterway using Loran information alone unless he had knowledge that the "fixed" errors (due to survey, approximation in calculation propagation velocities, etc.) has been compensated for.
- The mean square radial error was determined by calculating the error gradient, using the coordinates of the actual LORAN stations, and the time difference error as the RMS value of the time differences due to nominal values for transmitting system instabilities, receiver instabilities and errors, and atmosphere noise.
- Only one component of the error (cross-track) was of interest. This was approximated as the mean square radial error divided by $\sqrt{2}$.
- The result was an error gradient of 1.08 feet per nano-second and an RMS time difference error of 97 nsec. The RMS error for the cross-track component was taken as $(97 \times 1.08) / \sqrt{2} = 74'$.
- The phase II model will compute the N-S and E-W error components separately to define the error elipse. The cross-track component can then be extracted for any given channel course line.

FIGURE B-26.b. DISCUSSION OF σ_p MAP: LORAN C CASE

II.D Illustrative Example

The primary purpose of this example is to demonstrate an analysis of a waterway configuration consisting of successive straight channels and bends. A hypothetical channel consisting of three straight channel segments and two bends was used to show the relative effectiveness of the aid to navigation systems using the Phase I integrated model. This example does not, however, reflect the full scope of our analysis, but serves merely to illustrate straight channel, bend and risk models.

II.D.1 Problem Description

Figure II-10 illustrates the channel configuration and A/N systems available to the navigators along the eight-mile course. Channel segment 1 is a 2.5 mile straight channel with a center-of-channel range as the aid to navigation. Bend 1 is marked by buoys at the points of intersection on the inside and outside adjacent channel edges. Buoys along the right side, on channel segment 2, provide visual cues for the turn maneuver.

The second straight channel segment is three miles long and marked with two sets of gated buoys one mile apart. An additional set of buoys marks Bend 2 at the intersection of the two straight channel edges. The last channel segment is 2.5 miles long and marked by buoys on the left side of the channel only. Navigation from these buoys is by radar.

The Run and Observe model and Channel Bend model were used to propagate the distribution of vessels along the channel. The models were run sequentially, each providing joint distributions of cross-track position (P) and direction of motion (θ) for input to the next waterway model. The initial cross-track positions were uniformly distributed between $\pm$ 125 feet cross-track. Directions of motion were uniformly distributed from 0° to 5° toward the left edge of the first channel segment.

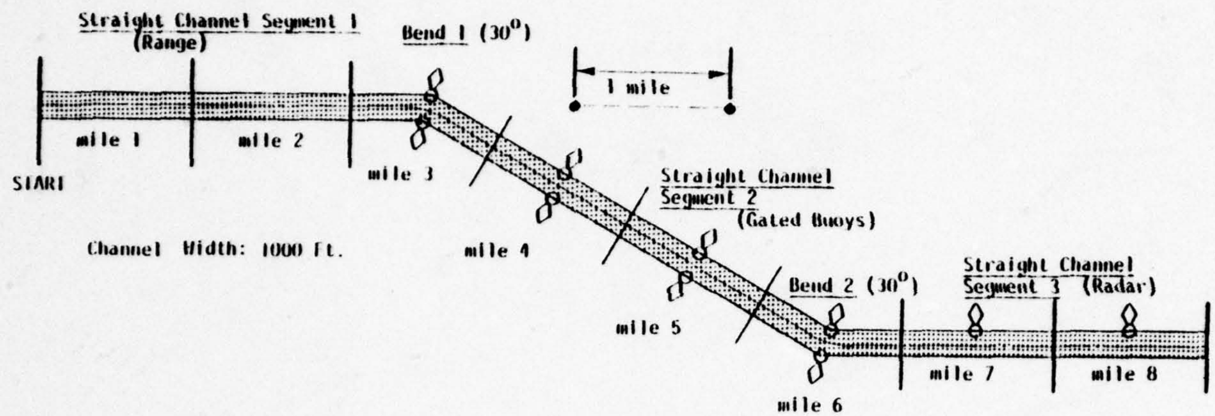


Figure II-10. Channel Geometry and A/N Systems Scenario for Illustrative Example

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The entire configuration and results are illustrated by the successive Figures II-11.a through II-11.h. The along-track scale was compressed in relation to the cross-track scale so that fewer figures would be needed to show the waterway configuration.

Illustrated on the figures are the 98 percent contours and 80 percent contours of cross-track position for the 1000 vessels. The 98 percent contours are the outside edges of the dotted regions displayed on the channel. The 80 percent contours are the inside edges of the dotted regions.

As discussed in Secion II.C.1, the cross-track position contours and the pilot decision time measure can be used to provide insight into the effectiveness of an aid-to-navigation system. The risk index which represents the number of the 1000 vessels with pilot decision times of less than 15 minutes is displayed along the channel edge at 1,500 foot intervals.

III.D.2 <u>Discussion of Results</u>

The cross-track position contours provide information concerning the location of the vessels and the risk index indicates the number of vessels required to change their direction of motion within 15 minutes to avoid grounding.

II.D.2.1 <u>First Leg</u>. The cross-track contours and the risk index show steady improvement as the vessels approach the range and the first bend. The sequence of risk numbers indicates that the transient at the beginning of the channel has not completely dampened when the vessels enter the bend.

II.D.2.2 <u>First Bend</u>. The vessels enter the first bend (Figure II-11.c) with small errors in their cross-track positions and with little need for course correction. This is shown by the risk index just before the vessels enter the first bend. Only .005 of the vessels have a pilot decision time of less than fifteen minutes.

A/N ILLUSTRATIVE EXAMPLE

Channel Segment 1
Mile 1

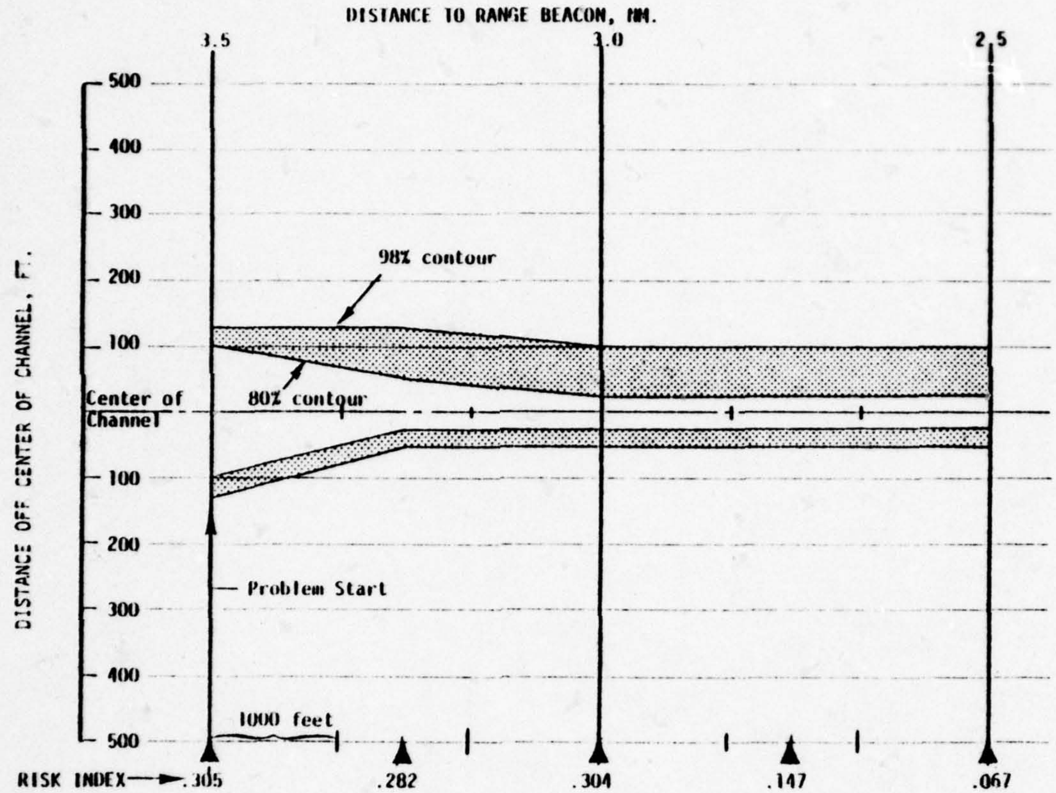

Figure II-11.a. Measure of Effectiveness of A/N Systems

A/N ILLUSTRATIVE EXAMPLE

Channel Segment 1
Mile 2

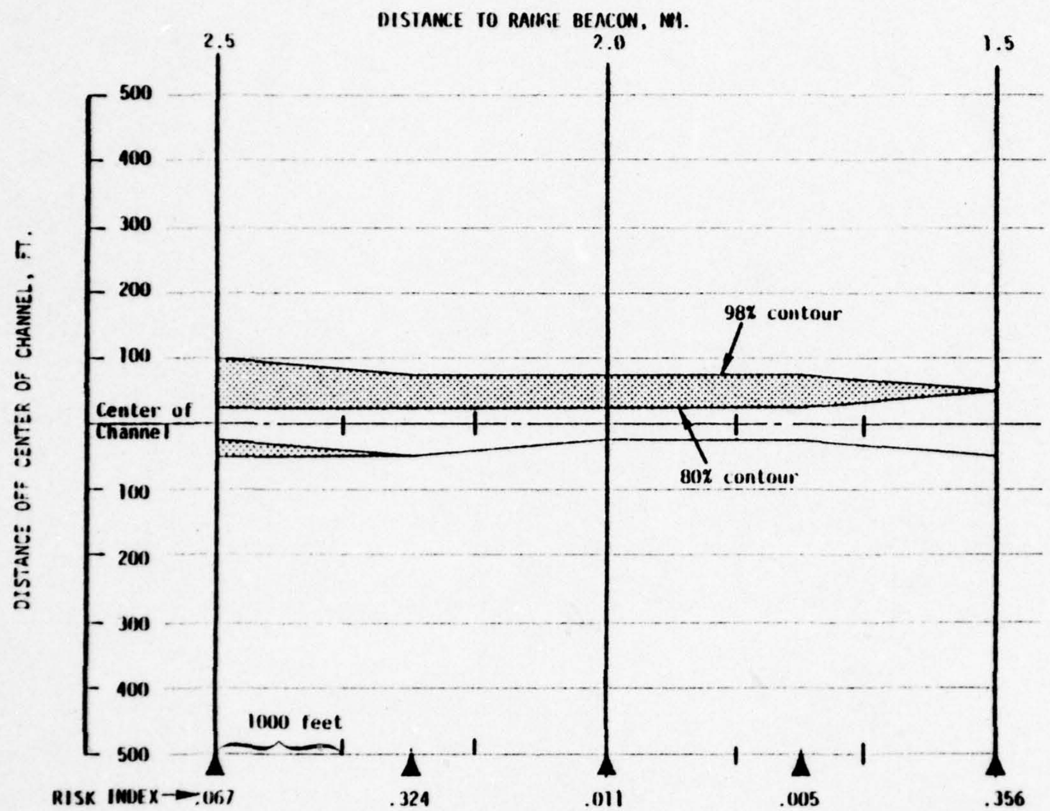

Figure II-11-b. Measure of Effectiveness of A/N Systems, Cont'd.

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A/N ILLUSTRATIVE EXAMPLE

Bend 1
Mile 3

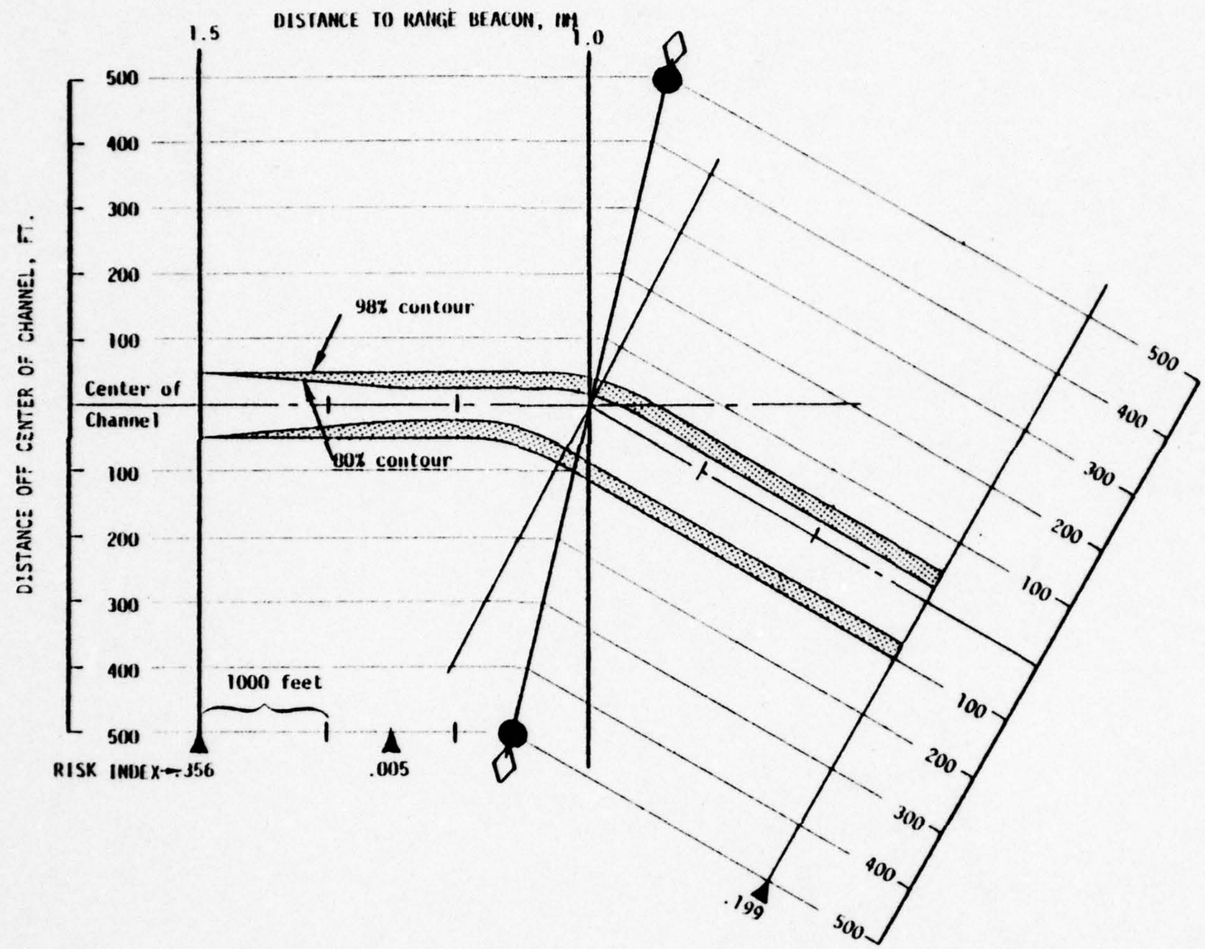

Figure II-11-c. Measure of Effectiveness of A/N Systems, cont'd.

A/N ILLUSTRATIVE EXAMPLE

Channel Segment 2
Mile 4

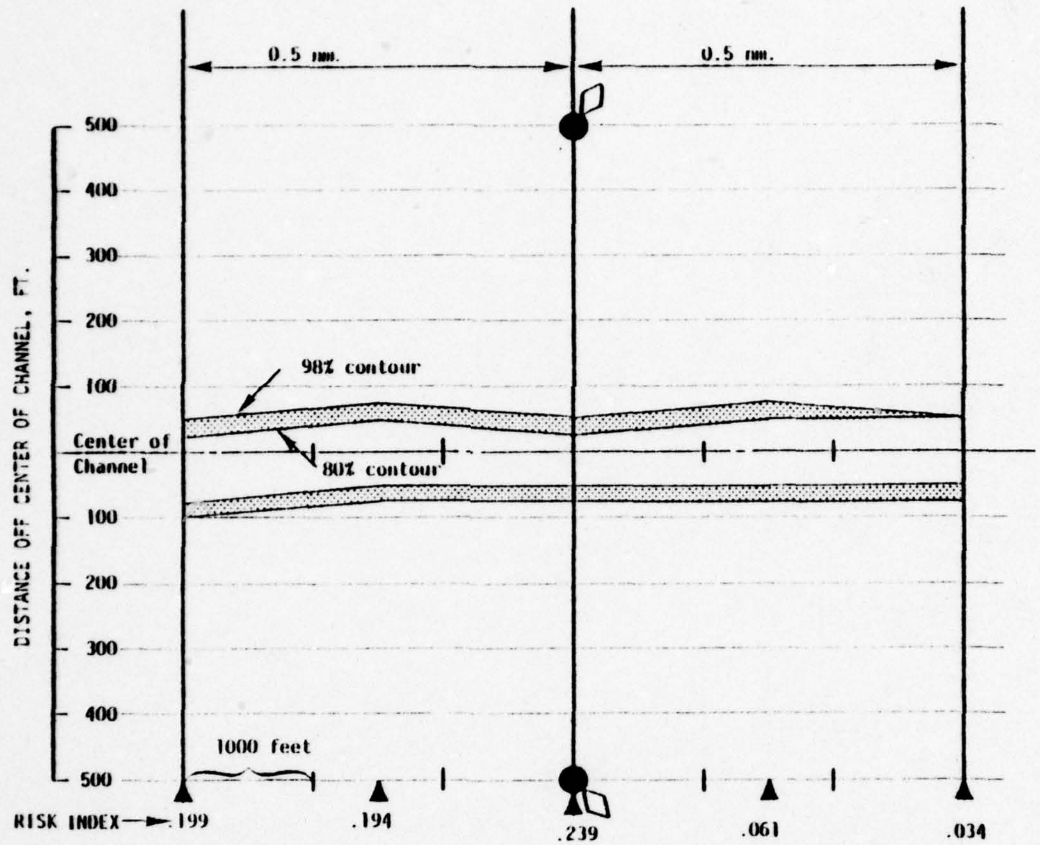

Figure II-11-d. Measure of Effectiveness of A/N Systems, Cont'd.

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A/N ILLUSTRATIVE EXAMPLE

Channel Segment 2
Mile 5

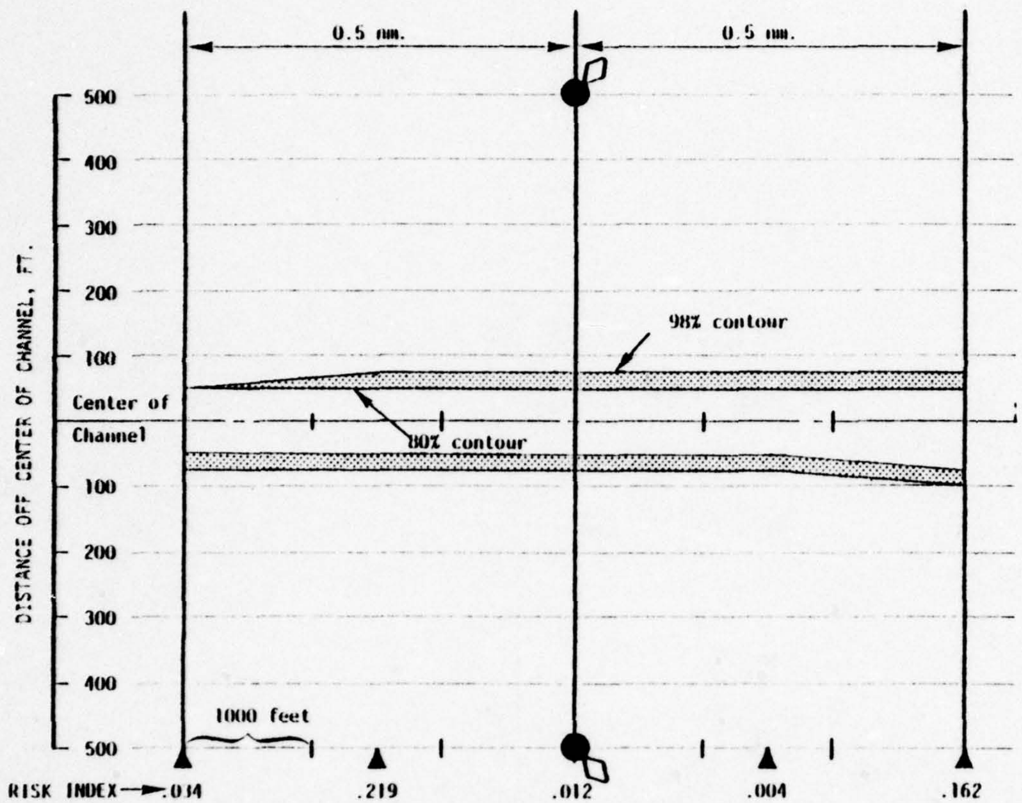

Figure II-11-e. Measure of Effectiveness of A/N Systems, cont'd.

A/N ILLUSTRATIVE EXAMPLE

Bend 2
Mile 6

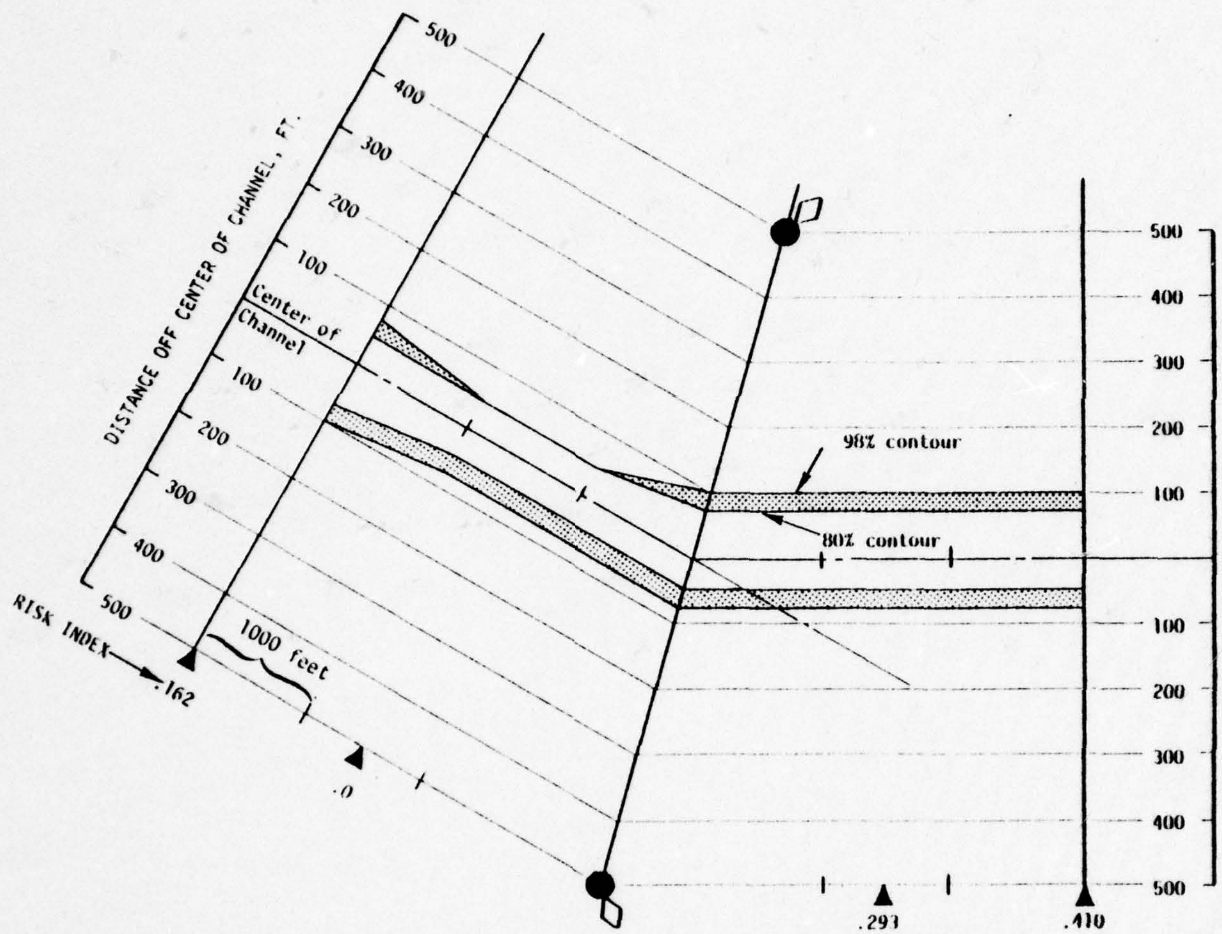

Figure II-11-f. Measure of Effectiveness of A/N Systems, cont'd.

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A/N ILLUSTRATIVE EXAMPLE

Channel Segment 3
Mile 7

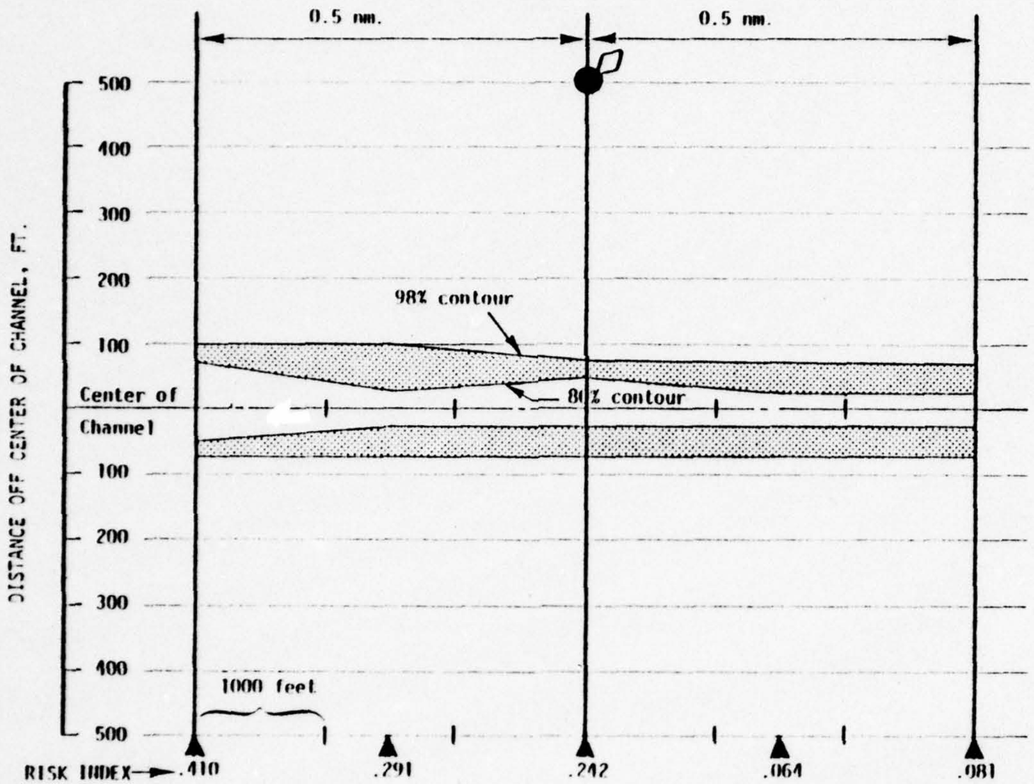

Figure II-11-g. Measure of Effectiveness of A/N Systems, cont'd.

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A/N ILLUSTRATIVE EXAMPLE

Channel Segment 3
Mile 8

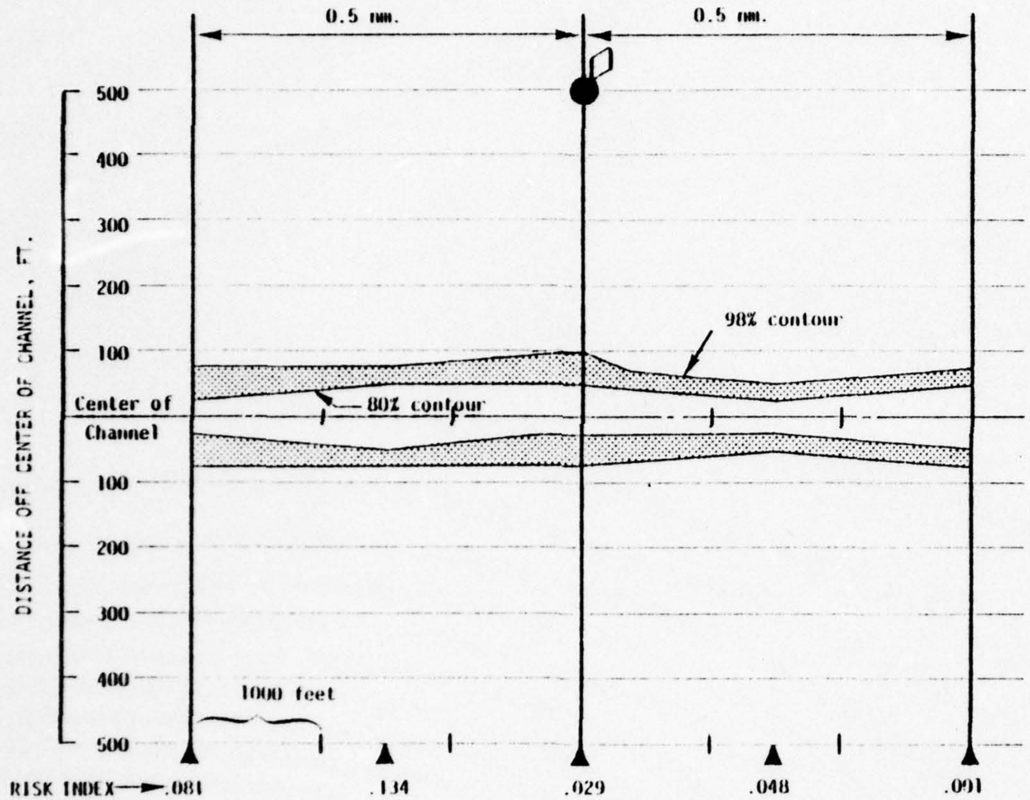

Figure II-11-h. Measure of Effectiveness of A/N Systems, cont'd.

The cross-track error of the vessels has increased considerably as they exit the first bend. The cross-track errors, as displayed by the 80 percent contours, have changed from ± 20 feet upon entering the bend to approximately 80 feet to the right and 20 feet to the left.

II.D.2.3 Second Straight Channel Segment. The vessels start with cross-track positions to the right of the desired track. The gated buoys provide the pilots with sufficient cross-track position information to cause the vessels to return to their desired track. The risk index numbers immediately after the bend shown in Figure II-11.d indicate that many vessels corrected their directions of motion after entering the straight channel segment. The vessels have gone through a transient stage in correcting their cross-track positions before leaving the second straight channel leg.

II.D.2.4 Second Bend. The vessels enter the second bend with relatively good cross-track position contours. The effect of the bend is to expand the cross-track position contours. This requires relatively large numbers of course corrections when entering the third straight channel leg.

The first two straight channel segments were characterized by fluctuating changes in the cross-track positions of the vessels. This was due to the nature of the information provided by the range in the first segment, and the gated buoys in the second segment.

II.D.2.5 Third Straight Channel Segment. The radar case illustrates improved cross-track positions, correlated to passing a buoy. This is due to the fact that radar provides very accurate cross-track information when abeam of a buoy if the desired track is near the center of the channel.

The sequential applications of the run and observe model and the channel bend model imply that a range, gated buoys, and radar having buoys on one side provide sufficient information for the desired track illustrated.

PAGES III-1 THRU III-36
Follows -MORE-

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III. REQUIREMENTS FOR PHASE II

This section outlines methodology development requirements for the Phase II program. The requirements are discussed under four major headings: modeling requirements; basic data requirements; model validation requirements, and special topics for investigation.

III.A A/N Model Refinements and Improvements

This section discusses refinements, improvements, and extensions of a modeling nature that will be required for the Phase II program.

III.A.1 Safe/Grounding Domain Refinements

The safe/grounding domain module will be completely automated. Currently, grounding domain values are output from a computer program as discrete points. These points are used to establish a polynomial curve which best describes in a least squares sense the grounding domain for the vessel. The coefficients of this polynomial equation are used as inputs into the straight channel control model, which outputs the distributions of pilot decision times. Thus far, in the straight channel risk calculations, angular velocity has been considered as zero. The inclusion of angular velocity will require the grounding domain be described by a sufficient number of polynomial coefficients so as to allow consideration of direction of motion, distance from the grounding constraint and angular velocity simultaneously. The number of equations that will be necessary will depend upon the accuracy of results that can be achieved by using interpolation techniques between the defined curves.

In addition to working out techniques for automating the grounding domain, certain refinements will be required.

The model inputs should be simplified so as to make the model user-oriented. Hydrodynamic coefficients of vessels, of various types, or under various loads, or in various depths of water, should be stored on a file that can be accessed based upon ship type, loading, depth of water, etc. Vessel characteristics can easily be coded using a single input number.

The model will include the capability of calculating the effects of wind, current, depth of water, as well as bank effects. The model can currently calculate shallow water effects using different hydrodynamic coefficients for the vessel. The model can be adapted to handle the suction forces acting on the vessel. A subroutine exists for combining current and wind effects with the maneuvering equations now being used. The instantaneous effects of changing currents and/or winds must be included. The model should likewise be adapted to characterize the cushion effects when the vessel is travelling near the edge of a channel.

The necessary inputs would describe the ship, its speed, the waterway geometry, and the environmental conditions such as winds and currents.

III.A.2 Human Factors Modeling Requirements

For convenience, two levels of model improvements are defined. These are referred to as model refinements and model extensions. The model refinements are improvements that can be made to the human factors models with little or no developmental work involved; the only reason they were not accomplished in Phase I was time constraints. Model extensions are those improvements that will require some developmental effort or human factors research to complete. The following two sections outline each of these areas in turn.

III.A.2.1 Model Refinements. *Skewed Distributions.* As discussed in Section II, the distributions of cross-track position

resulting from using the A/N to fix cross-track position are often skewed. Examples involving propagation of skewed errors are discussed in Appendix B. However, the error maps for Phase I were developed ignoring this skewness, and no provisions are available in the Phase I run and observe model to explicitly handle skewness. During Phase II we will modify the computation of probabilities in the run and observe model to explicitly handle skewed distributions. The propagation of skewed errors will also be refined, and the display of skewed distributions on σ_p maps will be formalized.

Run and Observe Decision Function Module. The decision logic for the straight channel run and observe model will be reevaluated during Phase II to ensure that the model is correctly interpreting the modeled errors, and to ensure that all of the important aspects of the mariner's decision to either change course or remain on the current course are included in the logic. We are not, of course, interested in individual mariner preference. However, the model should correctly treat (in a statistical sense) such items of the decision process as the region of cross-track position indifference in navigating a straight channel. One approach would be to set the decision up as a statistical hypothesis test, where the null hypothesis corresponds to the mariner's acceptance of his present course. Human factors data could then be obtained to characterize the propensity of mariners to accept courses that may be outside their indifference region, versus the propensity to make frequent course changes, some of which may be unnecessary. In this way the region of indifference could be statistically defined in terms of simplified human decision processes.

Run and Observe Course Correction Module. Several improvements to the straight channel, run and observe course correction module are required. First, the arbitrarily defined ship paths used in the Phase I model will be replaced by simulated ship paths from the ship maneuver model. The effects of water depth, ship type, and bank effects will automatically be included in the run and observe model by this

modification, since these effects are contained in the ship maneuver model.

Second, the strategy for performing the course correction should be reexamined. The present model arbitrarily specifies that the course correction should be completed in 1200 feet, and then distributes the portion of ships making course corrections over values of cross-track position concomitant with σ_p, and values of direction of motion less than the previous directions of motion of the vessels. Sensitivity analyses will be conducted to determine the effects of these approximations on the model results. If the effects are large, several options should be exercised:

- Specific course correction strategies should be exercised to evaluate the interactions between these strategies and the information from alternative A/N systems. This may indicate that some strategies are more appropriate for use with particular A/N systems than others.
- Human factors analyses concerning how mariners actually performed the course correction maneuver should provide a basis for modeling this maneuver in a more realistic way. If variations between mariners are obtained, this variation will be reflected in the module as statistical distributions, which would then be handled in the same way as the other model statistics.

Inclusion of these course correction module modifications should provide the straight channel run and observe model with a realistic course correction capability.

Bend Model. The Phase I bend model is rather limited concerning the observables used to initiate the first rudder change for the bend and monitoring the bend (see Section II.B.3.3). However, the model will operate using any distribution for turn initiation and turn

monitoring. Phase II model refinements will be primarily oriented toward developing a wide variety of options for these distributions. These options will be treated as alternative error maps for bends in the same way that σ_p maps are treated for the straight channel run and observe model. Thus, the major effort here will be directed toward generalizing the generation of bend error maps; the Phase I bend model is capable of using whatever error maps are generated.

Some attention will be directed to ensuring that the bend model can handle any strategy that the mariner might employ in negotiating the bend.

Sinuous Channel. Our human factors investigations have indicated that mariners view sinuous channels simply as a succession of bends. In this case, modeling the sinuous channel should be handled by a successive application of the bend model. However, special problems may exist concerning the observables for sinuous channels. We will direct human factors investigations to this problem and incorporate any deviation of results from the bend scenario connecting straight channels, if these investigations indicate a necessity to do so.

Miscellaneous Model Refinements. Some effort will be required to streamline the model execution and ensure accurate model output, especially the straight channel run and observe model. In particular, the effect of various cell sizes on the model output and running time will be investigated. The intention here is to assure that the arbitrary portions of the model, particularly model cell size, the size of steps, and the number of steps between printouts (see Appendix B), do not affect the information resulting from applying the model. This effort will be more of a sensitivity analysis than a model modification.

Running time for the Phase I run and observe model is less than ten seconds for most cases. However, with the addition of the proposed refinements and modifications, running time could be a consideration, especially when the run and observe model is integrated into

a total Aids to Navigation Model. During Phase II we will investigate the desirability of decreasing running time by selectively examining only those cells that contain a non-zero portion of the distribution of ships, or, for some cases, increasing the size of the incremental distance step.

III.A.2.2 Model Extensions. *The Constriction Scenario.* Although constrictions were not explicitly modeled during Phase I, the present model may be capable of assessing this navigation scenario with little or no modification. The constriction appears to be a case of more stringent requirements placed on cross-track position keeping, coupled with alignment requirements upon entering the constriction. It may be necessary, however, to explicitly examine and model the observables for the constriction task. This will necessitate exercising the usual analysis scheme of identifying the observables (which may be similar to the observables for gated buoys), relating the observables to the navigation variables (which will include cross-track position, but may also include other factors such as the heading of the ship as it passes through the constriction), developing the errors for the observables (from human factors experiments), and developing the error map for the constriction. The role of A/N for this scenario may be to aid in aligning the ship before entering the constriction. We are not excluding the possibility that there may be unique features of the constriction problem that would require additional modeling.

Entering a Port or Waterway. The Phase I model may be capable of treating a large portion of this navigation scenario, also. The waterway entrance scenario should be largely a problem of channel alignment in the presence of environmental factors such as wind and current, the effects of which are not completely known to the mariner. The Phase I run and observe model treats the alignment task as a transient caused by a set of initial conditions of cross-track position and direction of motion. These initial conditions can be specified as resulting from the effects of environmental factors which are uncompensated for by the mariner.

However, there may be aspects of the constricted waterway alignment task that are unique to this navigation scenario. One possibility is the inclusion of the role of specialized A/N to aid in identification of the waterway, and alignment upon entering the waterway. This navigation scenario will be analyzed on the same basis as the analyses described in Section II.

Multiple A/N Systems. The primary questions to address here concern how mariners utilize information from several sources, e.g., from several A/N systems. Although this is primarily a human factors analysis, the results of that analysis will be incorporated into the A/N models. The questions to be addressed concern how information is prioritized and how the information is utilized to make navigation decisions. Possibilities include using information from the system that provides information with the smallest error, or perhaps information that is provided closest to a reference point. Our pilot interviews have indicated that visual information takes precedence over information from a radio A/N system in most cases. There may, however, be preferences that are relatively independent of the errors in the observables (e.g., pilots may prefer to use gated buoys over ranges when both are present, even though ranges provide information with smaller errors). We have no basis for making this assertion, but it is a possibility. Buoys provide reference points at the channel edges and center, while conventional ranges provide a reference point only in the center. Also, information from several sources may be factored together in some as yet unknown way. It is important to address these questions not only to assess how combinations of A/N systems fit together, but also with respect to the problem of meshing several available observables on the error maps.

Environmental Factors. The Phase I model does not explicitly treat the environmental factors such as wind and current, or water depth and bank effects. Wind, current, water depth and bank effects will be included in the ship maneuver model; therefore, their inclusion in the safe/grounding domain portion of the model will simply be a matter of

exercising these options. However, the inclusion of these effects into the straight channel and bend models is a high priority requirement for Phase II.

The effects of uncompensated wind and current are important elements of the transient portion of the straight channel run and observe model. These effects could cause biased directions of ship motion on entering a channel or navigating through a constriction. The Phase I model is initialized by assuming the resultant of an uncompensated wind and current as a biased set of directions of motion for the distribution of vessels (Section II.B.3.3). In Phase II it will be required to translate explicitly a given uncompensated wind/current combination into biased directions of motion and/or cross-track positions. The effect of various A/N systems in allowing the mariner to navigate in the presence of these environmental factors can then be assessed. Also, the capability of treating varying wind and current along a channel will be implemented. Again, inclusion of these environmental effects in the ship maneuver model will greatly facilitate this model extension.

Motion Detection. The Phase I straight channel run and observe model does not include the possibility that mariners may detect ship motion in real time. Hence, the designation "run and observe." It is possible, however, to include real time detection of ship motion in this model (the name of the model would then be changed). Ship motion can be detected in real time under certain circumstances, e.g., close to a buoy or reference point, or when the cross-track motion is large enough with respect to a range or line of buoys. Motion of the jack-staff can be detected with respect to a differentiated background, but it is difficult to separate linear motion from rotational motion in this case. The mariner's ability to detect motion does provide bounds on realistic directions of motion that the run and observe portion of the model need consider. Real-time detection of direction of motion will be incorporated in the Phase II straight channel model.

Information from Non-A/N Sources. The Phase I program concentrated on modeling information from the A/N. During Phase II it will be necessary to include information from sources other than the A/N into the human factors models. Like the information from the A/N, this information will enter the model at the observable stage. No major revisions are expected as to how the information will be handled in developing error maps, or in modifications to the straight channel or bend models. Defining the role of this information and how it meshes with the information from the A/N is essentially a human factors task, and is discussed in Section III.B.2. Modeling the information will serve to modify the error maps.

Our Phase I analysis has indicated that visual information from sources other than the A/N will probably result in ranging, bearing, or direct distance observables. This is substantiated by pilot interviews. The very fact that pilots use information from non-A/N sources may indicate a possible deficiency in the information available from the A/N. On the other hand, A/N information may not be necessary when sufficient information is available from other sources. A point in reference is the information provided by a constriction such as a drawbridge. Sufficient information may be available from the constriction itself to satisfy the requirements for navigating through the constriction. This analysis will include not only information, but noise from other sources also, e.g., background lights interfering with range lights during night navigation.

The role of navigational aids such as compasses will also be assessed.

Traffic Facilitation. The Phase I analysis was primarily directed toward assessing risk. Only the theoretical basis for a traffic facilitation measure was developed during this phase. This measure is described in Appendix B. Although little quantitative work was completed using this measure, it is evident that the two major contributors to

traffic facilitation are the speed at which vessels may transit a waterway and the propagation of times during the year when environmental conditions permit any transit at all. Many factors constrain speed which are outside the realm of improvement by A/N systems. However, if speed is limited by visibility, the A/N system could possibly have an impact. Likewise, many environmental factors which prohibit transit are not influenced by the A/N (e.g., tides); but visibility is one environmental factor where this is not the case. Thus it appears that the primary determinant of traffic facilitation is visibility. The traffic facilitation index is to be evaluated on this basis.

The Phase II modeling effort for traffic facilitation will be based on the above. The only major unknown at this point is the effect of visibility on ship speed and the decision to transit the waterway or not. Part of the Phase II effort will involve structured interviews with pilots to attempt to extract this information. The model will be developed based on these data. Another portion of the analysis will involve estimating the visibility statistics for a given port area. To the extent that this information is available, this will form the basis for assessing the potential impact of a given A/N system at that port.

Risk Measures. The measure of risk developed during Phase I is the remaining pilot decision time at a given place in the navigation scenario. Other risk measures may be appropriate to supplement the pilot decision time, and will be investigated in Phase II. One possible risk measure that will be investigated in Phase II is the size of the allowable indifference region in navigating a scenario. The run and observe navigation process can be viewed as a series of assessments and course corrections. The frequency with which course corrections are made depend on the mariner's perception of the navigation situation, and his willingness to trade off risk with frequent course corrections. The band of indifference is a direct result of this trade-off; it results

from the judgment of the mariner to be unconcerned about course correction within this band. A measure of risk then might be the size of the band of indifference that could be tolerated with a given A/N system. For instance, an A/N system with reference points at the channel edges might result in a significantly larger band of indifference than a system characterized by large errors in cross-track position at the channel edges. The A/N system with reference points at the channel edges would allow precise cross-track position determination at the very place where it is needed the most, thus allowing the mariner to be comfortably closer to the edge (thus increasing the allowable band of indifference). This measure will be investigated and quantified in Phase II.

Nighttime Navigation. Although the Phase I program was primarily concerned with daytime navigation, some initial work was accomplished on nighttime navigation. Pilot interviews suggested that nighttime navigation was generally more difficult than daytime navigation. Preliminary work with a channel perspective simulator suggested that pattern recognition is a technique employed for nighttime navigation, as well as daytime navigation. However, a detailed investigation of nighttime navigation is required for Phase II. This investigation will be conducted with respect to two viewpoints:

- How extensive is pattern recognition employed in navigating during the night? Are there other aspects of nighttime navigation that are important to the model?
- What are the elements of nighttime navigation, especially using lighted buoys, that make the problem difficult or easy?

Elements of the latter question involve the effects on ability to navigate of duration and frequency of blinking buoy lights; synchronized patterns of lights; and pattern recognition in a high noise environment.

Many of these questions will be addressed using the channel perspective simulator developed in Phase I. They all involve modeling of experimental results, which will be undertaken in Phase II.

III.A.3 Model Integration

This section discusses the integration of the various aspects of the methodology into the Aids to Navigation computer model. Completion and verification of this model are viewed as the final objectives of the Phase II program.

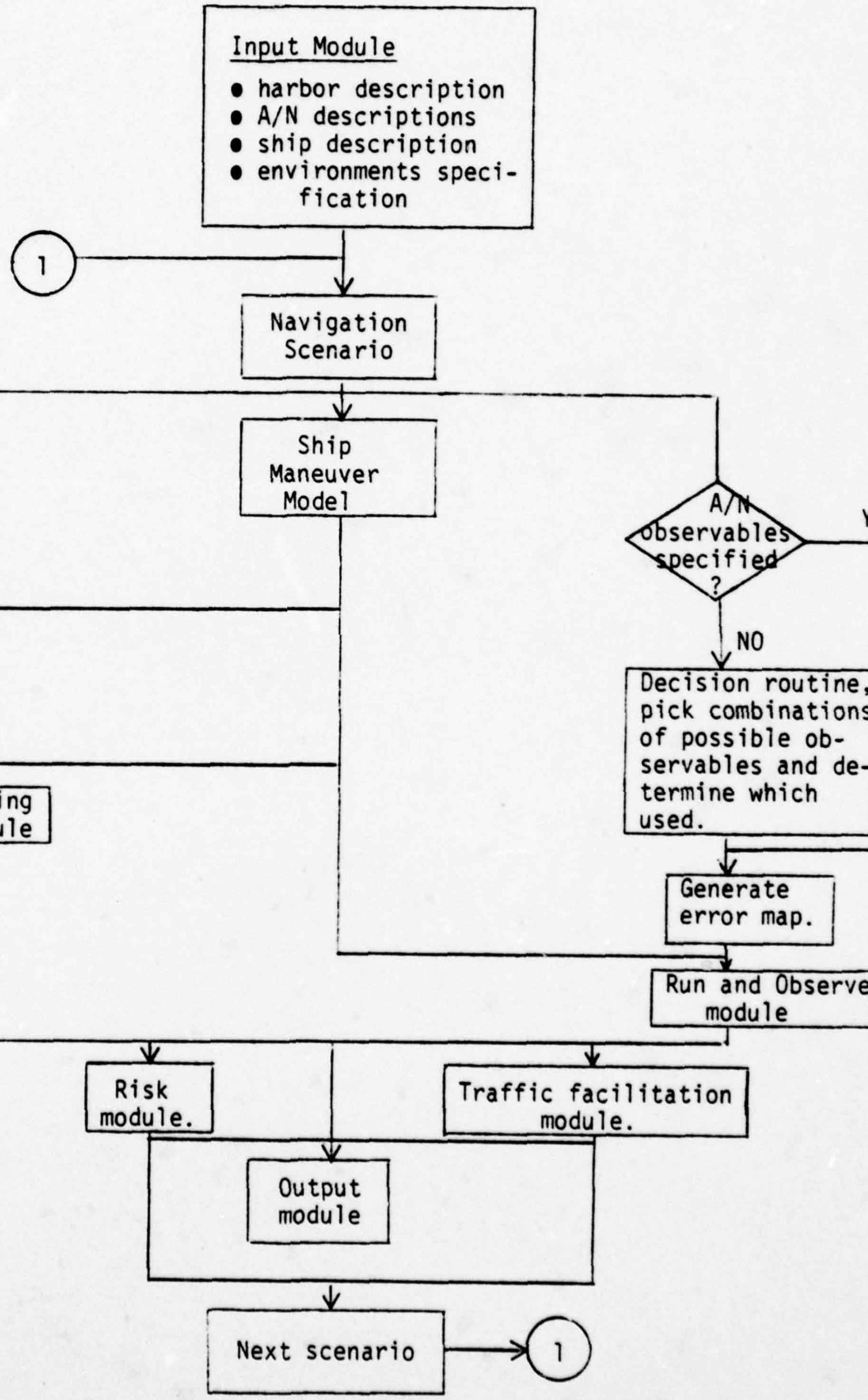
The major pieces of the methodology to be integrated are: calculation of safe and grounding domains; generation of error maps; exercising the navigation models for the navigation scenarios, e.g., run and observe, bends; and calculation of measures of risk and traffic facilitation. The inputs to the integrated model are to be: a description of the waterway in terms of a succession of navigation scenarios; the physical description of the scenarios, e.g., water depth, channel width, etc.; a description of the A/N for each scenario; a description of vessel type and characteristics, including height of eye; a characterization of mariner choice criteria such as band of indifference and course correction; environmental factors such as wind, current, visibility, and day or nighttime navigation; and a characterization of information from sources other than the A/N (including noise). Optimal outputs would be available including the risk and traffic facilitation measures at any places on the scenarios; selected summary outputs from the navigation models such as, for instance, probability contours of cross-track position resulting from the information supplied by the A/N system under investigation; error maps for the navigation scenarios; or safe/grounding domains at selected places on the scenarios. The amount of input required and output generated, of course, can be adjusted by including "standard" cases that would be exercised automatically when not specified. For instance, a "standard" ship type might be run if no ship type was specified as input. Also, it might be appropriate

to analyze only the probability contours from the run and observe model for one navigation scenario, and this would be an option. The options available will be tailored to the requirements of the U.S. Coast Guard.

Figure III-1 illustrates the functional blocks of the Aids to Navigation model. Each of these functional areas are discussed:

- The input module allows specification of the harbor in terms of a sequence of navigation scenarios; specification of the A/N type for each navigation scenario in the sequence; specification of ship type; specification of choice criteria, and specification of environment.
- The harbor is modeled as a succession of navigation scenarios. Each navigation scenario is analyzed in turn.
- For each navigation scenario, the desired ship track and safe/grounding domains are calculated. The ship maneuver model is used for this calculation.
- Two options would be available concerning modeling the information from the A/N systems employed in a scenario. The observables for the A/N may be specified as input to the program, in which case an error map is generated directly from these observables. Or, a routine would be available to postulate the possible observables from a particular A/N system and use the set that optimizes some programmed criterion If more than one observable could be used, for instance, to estimate cross-track position (e.g., direct distance estimation or match visual angles from gated buoys), the routine would choose between the alternatives according to some preestablished criterion. This criterion may be formulated based on the relative ease of

FIGURE III-1. INTEGRATED A/N MODEL



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psychological tasks, or the observable that gives the minimum variance estimate.

- An error map is generated using the mathematical relationships between the observables and navigation variables. An appropriate error propagation technique will be used that will preserve a sufficient amount of information to characterize the mariner's ability to fix the navigation variables of interest.
- The navigation model for the navigation scenario is exercised.
- The risk and traffic facilitation measures are estimated.
- Output from the model will be as specified as an input option. It is anticipated that a wide variety of output options could be made available, including exercising and outputting information from only part of the model, e.g., from the grounding domain portion, or an error map.

It is anticipated that significant input from the U.S. Coast Guard concerning user requirements of the Phase II integrated model will be obtained. The model will be tailored to satisfy the diverse requirements of the Coast Guard in as far as possible.

III.B Basic Data

The refinement and extension of the model will in many cases depend on the acquisition of human factors data. We still need to identify observables for some tasks, and we need to quantify the error associated with some of the observables already identified. We also need to consider the choice and decision processes associated with the use of extractable information.

III.B.1 Observables for A/N

We believe we have a fairly complete description of the observables associated with straight channels, and we need merely to be open to other possibilities during model verification (see Section III.C). For negotiating bends, we need a more precise specification of "relative motion of objects past the bow" as an observable. Pilot comments indicate that the objects should be within about 10^{o} of the bow, and that water is a sufficient "object" if others are lacking. We need to know how the judgment process is affected by type and exact location of objects. For negotiating bends, we also need a clearer statement of the observable associated with watching the inside turn buoy.

A number of scenarios have been treated only lightly. There is some suggestion that observables already identified will suffice for some of these. For example, pilots report using the visual angles of bridge abutments, and ranging on bridge superstructure, for approaching a constriction. However, for situations only partly studied, we need to make a careful search for other observables. One for which there is an obvious lack is the use of a sea buoy in approaching a channel entrance.

In addition to completing identification of observables for visual A/N, we need to identify those made available through the use of electronic aids. We have made only the most preliminary identification

for use of radar, and we need human factors data to test our choices. In general, the problem of dealing with electronic aids is that the user's task depends less on the A/N than on the equipment he uses. In order to characterize use of A/N for a particular class of vessel, it will be necessary to have some notion of the availability of different kinds of equipment on that class. Then the relevant human factors information can be determined for the equipment typically available.

III.B.2 Using Sources Other than A/N

Our treatment so far has been almost exclusively concerned with A/N in isolation, as though channels existed in infinitely broad waterways. It is obvious that A/N do not exist in such isolation. Context may be important, as suggested by pilots who said that it is easier to detect lateral motion by watching a buoy against a background than by watching the buoy alone. Furthermore, objects other than A/N may serve as exclusive "aids," as when swing is judged by watching trees go by, or when a range of opportunity is used.

When the role of A/N in a harbor is assessed, it will be necessary to take into account the context provided by the harbor. Accordingly, we will have to characterize non-A/N sources in terms of the observables they provide, particularly the observables provided by using them in conjunction with A/N. We need to assess pilots' use of natural aids, with special attention to whether such aids provide primary navigational information or whether they are chiefly used to confirm the information provided by the A/N (as by indicating whether a buoy has drifted off station). We may need to classify natural aids in terms of their salience, as by determining which types are universally used and which types are idiosyncratic to individual pilots.

III.B.3 Statistical Characterization of Observables

Once observables have been identified, it is necessary to describe the error associated with their use. In general, the distribution of error is not fixed for a given observable. Rather, as the observable's

appearance is made to differ more and more from what its appearance would be at a reference point, the probability of a large error in using the observable increases. A description of the error distribution as a function of observable appearance is needed for each observable.

In general, such error functions are not available from standard psychophysical literature. Only in the case of visual angle ratios have we been able to extract sufficient information to generate a reasonably good equation. Even for such a seemingly simple task as direct distance estimation, extant studies do not provide adequate information for any cue except visual angle subtended by an object of known size; and we have evidence that that cue is not the correct observable for pilots' estimation of distance over water.

We have regarded error in using an observable as being the result of inherent variability in human perceptual processes. Psychologists have developed standard experimental designs for measuring such variability. The application of such a design is illustrated by an experiment performed under this contract. The purpose was to measure sensitivity to change in openness of a range. We selected several values of the observable (degrees of openness, combined with different vertical separations of the range objects). For each value, we measured observers' ability to detect small differences in the openness of the range. Based on the number and kind of errors made, we were able to estimate the standard deviation of the error distribution at each value of the observable. A least squares curve fit then provided an equation describing error as a function of the observable. (The experiment is described more fully in Appendix A.)

Experiments designed to quantify error can also assist in choosing among alternative possible observables for a given task. For example, the study just mentioned showed that error, expressed as change in slope, increases linearly with slope. It also showed that, once slope had been used to predict error, prediction could not be improved

significantly by adding other descriptions of the observable. Furthermore, when error was expressed as change in the horizontal separation of the range, both horizontal and vertical separation contributed significantly to its prediction. Taken together, these results suggest that openness of a range is best characterized in terms of slope, rather than in terms of horizontal separation.

III.B.4 Perceptual Variability vs. Use of Information

If performance were a function of perceptual variability only, then a navigator would be constantly adjusting his ship's motion. Even when the ship was exactly where he wanted it to be, error in perception would often result in its being perceived as slightly off, and a correction would be made. Clearly, then, perceptual variability is not the only factor affecting the position and motion of a ship, even when a navigator is trying to steer as accurately as possible. He must have some means of deciding when to make an adjustment.

There are several possible ways of treating choice processes. One option arises from signal detection theory. In deciding whether two stimuli (e.g., two successive observations of an observable) are the same, an observer recognizes his own uncertainty and establishes a criterion: he will assume they are the same unless they appear to be different at least by a certain prespecified amount. The criterion could be set by the observer so as to create, for example, a low fixed probability of "correcting" incorrectly—i.e., of adjusting course when on the desired track, or of adjusting in the wrong direction. The probability for any arbitrary criterion, and hence the criterion actually chosen, depends on perceptual variability.

An alternative treatment is to assume that the mariner categorizes the observable into discrete steps, much as a person trying to use a faceless clock might assign the position of the minute hand to to the nearest remembered five-minute mark. A course correction would be made whenever the observable was judged to have crossed a category

boundary. If the categories were of equal width, then the probability of incorrectly assigning the observable to a category would be a function of the perceptual error associated with the observable. Alternatively, the category widths could be adjusted so as to create a constant probability of confusion between adjacent categories, with results very similar to those for the signal detection approach suggested above.

A third possibility, the one that is currently modeled, is to allow for the existence of a band of indifference. Rather than select a desired track, the mariner may select limits on both sides of such a track. As long as he is within those limits, he need not make any adjustments. From points near those limits, his judgment of whether he has strayed outside will be subject to error, that error again being determined by perceptual variability. A refinement of this option would apply signal detection theory to the establishment of a criterion for deciding that he has crossed over one of his limits.

All of the options discussed have in common the creation of limits on either side of any selected track. They differ only in the rationale for setting those limits, and consequently in the manner in which they are chosen. The run-and-observe control model we have developed can treat any such option. What remains is to select the appropriate one, a choice which is both philosophical and empirical in nature. The philosophical question has to do with the purpose of the model. If in practice the mariner actually has a band of indifference, for example, safety may depend on the bandwidth as well as on the aids. If bandwidth increases with better aids, a measure of safety may be insensitive to improvements in the aids because the increased bandwidth undoes their benefits. It becomes necessary to decide whether to model the aids with respect to their potential when mariners are being as precise as possible, or whether to model them with respect to probable actual use.

As noted above, the run-and-observe control model can handle any of the alternatives, so it may not be necessary to make a final choice; whether to model optional or actual use could be left as an

option in the model. Regardless of decisions on that point, model verification (see Section III.C) will depend on a version reflecting actual use. Therefore, either for the sake of the model itself, or for the sake of subsequent testing of the model, it will be necessary to collect data on the choice processes actually used. Such information will have to include not only the method of selecting limits on ship position, but also the strategy used for correcting position. The possible influence of A/N on these choice variables is also unknown.

III.C Model Validation

Our model consists of a collection of components operating together. It is necessary not only to test each component, but also to validate the model as a whole. In the last analysis, the model should predict performance in simulator tests or sea trials. While exact numerical conformity of predictions and performance need not be demanded, certainly the model should correctly predict which changes in the aids to navigation will improve performance, which will make it worse, and which will have little effect; and the general magnitude of predicted effects should conform to the magnitude of actual effects.

Both the human factors portion and the ships operation portion of the model are subject to validation tests. The former is amenable to simulator tests. The latter would require sea trials, but fortunately most of the validation for the ships operation portion has already been done. That portion of the model is based on equations developed by Dr. H. Eda, and he in turn has validated his work against sea trials. It has therefore been sufficient to show that the output of our ships operation program conforms to the results of Eda's work, as well as to the results of ship maneuvering models currently used by the U.S. Coast Guard. The validation of the previous work provides validation for ours.

The approach to human factors model validation was suggested at the beginning of this section. Human factors analysis will generate a set of testable hypotheses, hypotheses expressed in terms of which aspects of A/N can be changed without changing performance and which aspects will have substantial effect when changed. Although simulator trials were suggested above as the ultimate test of a complete model, most human factors hypotheses will be testable on a much smaller scale in a laboratory setting. Laboratory testing is considerably cheaper than simulator testing, and it has another important advantage. Laboratory testing allows effects to be

isolated and hypotheses to be tested individually. Thus, when a laboratory test fails to confirm a model, it provides some indication of what part has broken down, and the defective aspect of the model can be corrected. By contrast, when simulator performance fails to correspond to predicted performance, it merely indicates that one or more components of the model are incorrect, but it does not show which one.

A laboratory approach to model verification can be illustrated by means of the informal experiment cited in Section II.B.2.1. The experiment compared ability to estimate cross track location in a simulated channel when the channel was marked with either gated or staggered buoys. Our original human factors analysis suggested that visual angle ratio was the only observable responsible for making the center of the channel into a reference point for the task. Hence, analysis generated the hypothesis that performance would be sensitive to whether buoys were gated or staggered. Specifically, since gated buoys do not produce equal visual angles port and starboard from the channel center, the hypothesis was that error would be greater in the center of channel than elsewhere for staggered buoys, whereas it would be lower at the center of channel than just off-center for gated buoys.

The results of the informal experiment are displayed in Figure III.2. Performance does not seem to be much affected by whether the buoys are gated or staggered, and there is a reduction in error at the center for both conditions. It so happens that we were seriously considering the possibility of a slope matching as a second center-of-channel observable at the time we ran the experiment, and it is certainly the case that an informal experiment run on previously unused equipment with a single observer is merely suggestive, and is not sufficient to clearly test the model. The principle of a laboratory test of hypotheses is well illustrated, however: a well controlled experiment exhibiting similar results

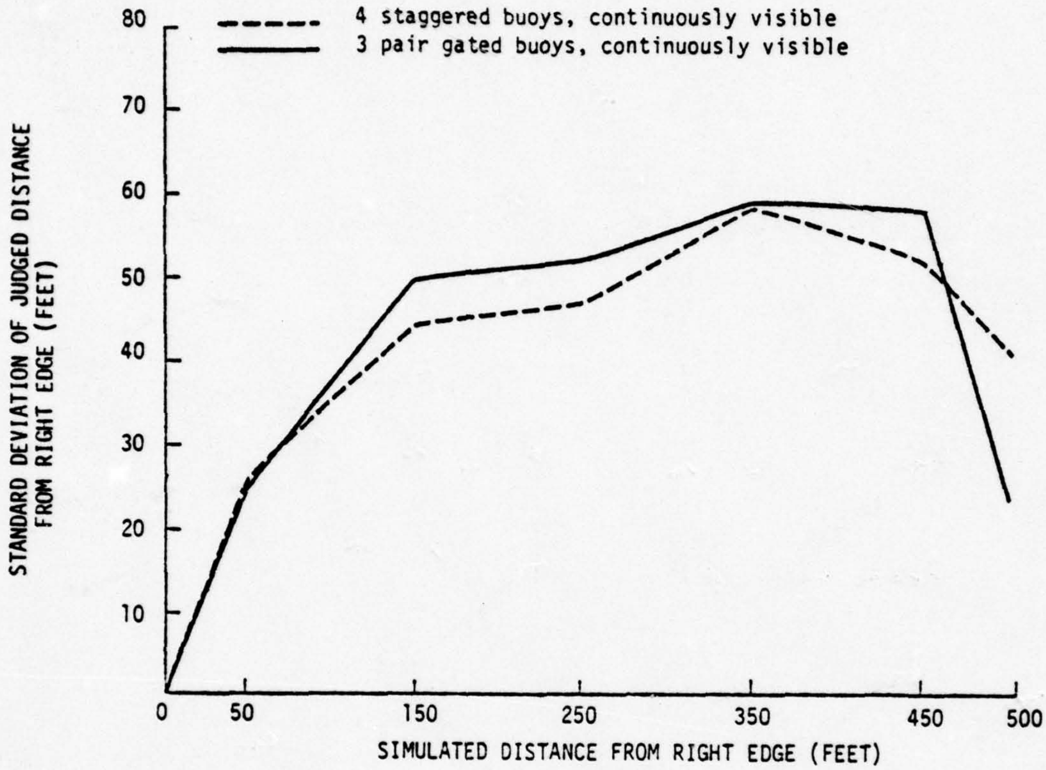

FIGURE III.2 ERROR IN JUDGING CROSS-TRACK LOCATION IN A SIMULATED 1000-FOOT CHANNEL FOR GATED AND STAGGERED BUOYS

would show the incompleteness of an analysis in terms of visual angle ratio as the only center-of-channel observable, and it would clearly point to the need to identify an observable with low center-of-channel error which was applicable to staggered buoy configurations.

The same informal experiment can be used to illustrate the possibility of testing the model quantitatively. Figure III.3 shows the results of the experiment for gated buoys, along with the predicted error presented in an error map for gated buoys in our January report, using slope as the observable at the edge of the channel and angle ratio as the observable near the center. Again it would be improper to make too much of the actual results of the experiment in question; but the fit, while it could use improvement, is not too bad (especially since the error function for the slope observable in the January report was merely an educated guess). More refined predictions can be compared statistically for goodness of fit to data from more refined experiments, providing an indication of the adequacy of the modeling and hints concerning the direction of improvement.

While laboratory experiments are often better as well as less expensive means of validating the model, simulator tests will sometimes be necessary. It would also be prudent to compare the results of existing simulator runs to predictions from the model, since all that would be required would be to run the model using the A/N previously simulated. Correspondences would increase confidence in the model, and discrepancies would show the need for additional laboratory tests of analytic work.

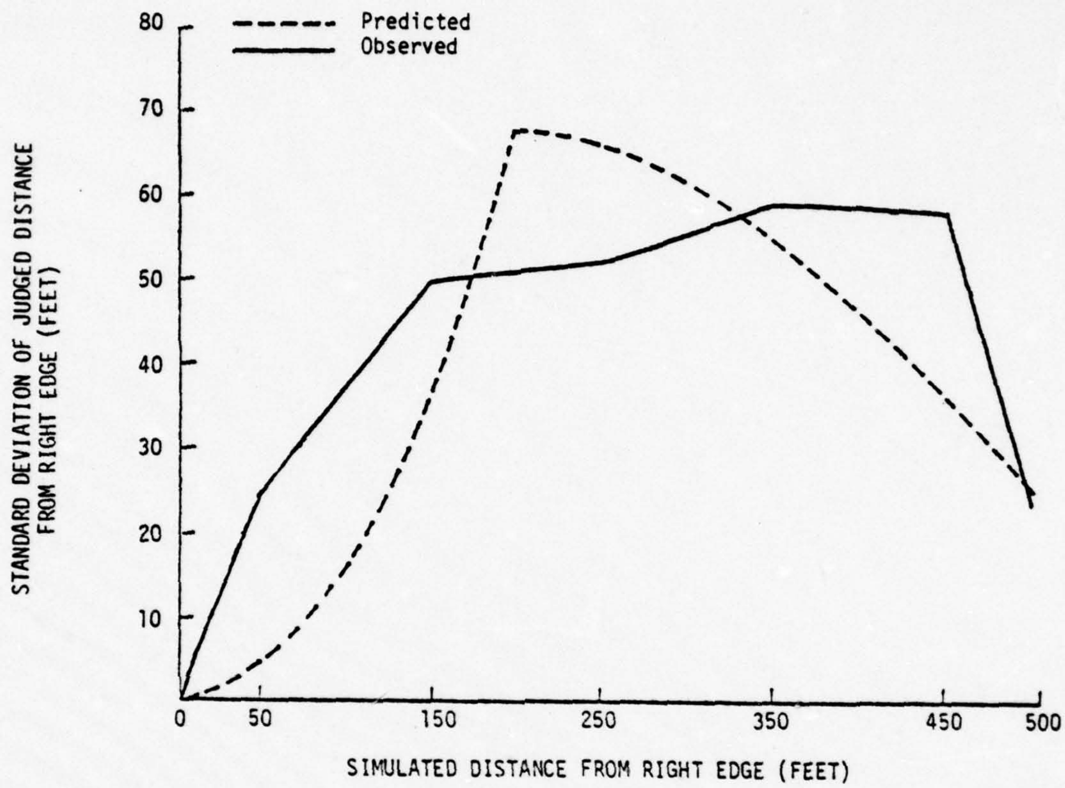

FIGURE III.3 PREDICTED AND OBSERVED ERROR IN ESTIMATING CROSS-TRACK LOCATION IN A SIMULATED 1000-FOOT CHANNEL MARKED WITH GATED BUOYS

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III.D Special Topics for Investigation in Phase II

III.D.1 Detection and Identification of Aids to Navigation

III.D.1.1 The Detection and Identification Problem. The cognitive processes used by mariners to derive information from aids to navigation are described in Section II without explicit treatment of the problem of detection and identification. These aspects may have significant influence on safety and traffic facilitation, and will affect the cost of aids to navigation. Accordingly, the Phase II effort will include tasks to quantify the relationship of detectability and identifiability to the navigation process.

Detection and Identification of Radar Aids. The detectability of an aid by radar is largely deterministic, given data on its cross-section, reflector geometry and any active emissions. Identification of electronically passive or uncoded aids requires the correlation of the relative positions of multiple targets on the display, including uncharted objects (e.g., other vessels). Data relating directly to the ability of a radar operator to effect such correlation has not been found to date. There is extensive data on pattern recognition capability, but that analyzed to date does not appear directly applicable to the radar problem. Further, the varying capabilities of radar installations will have an impact on the detection and identification task.

Active coded transponders make early positive identification nearly a certainty, and facilitate orientation of the mariner, particularly when making a landfall.

Detection and Identification of Visual Aids. The detectability of visual aids as a function of size, shape, color, reflectivity, luminous intensity, etc. under various ambient conditions which affect visibility can be calculated with some precision if the characteristics of the background are defined. Identification involves a number of related variables which include context and uniqueness. Positive

identification of at least one buoy or beacon is usually needed for the mariner to make a transition from plotted positions to direct visual observation, as when approaching a harbor entrance. Multiple aids, many of which appear roughly similar in characteristics, compound the problem. In interviews with pilots, there were indications that limited visibility was often desirable at night—it masked the background and distant aids, thereby simplifying the task of identifying those of immediate concern.

III.D.1.2 Objectives of the Phase II Investigation. The objectives of the Phase II tasks relating to detection and identification are:

- Define the characteristics of aids to navigation which hinder or facilitate detection and identification.
- Quantify the probability of correct identification as a function of characteristics, ambient conditions, context (patterns, numbers, background), distance and duration of observation period.

It is obvious that day and night conditions will be separate for visual aids, but that the radar case will be independent of visibility. However, the potential synergism of concurrent or alternate observation by radar and visual means will also be addressed.

It is anticipated that all basic data relating to detectability will be available in the psychophysical literature, but that some experimentation will be required to accurately quantify aspects that are unique to the aids to navigation problem. In particular, the effects of duty cycle and period for lighted aids does not seem to be adequately covered.

Experimentation is necessary to quantify key aspects of identification. A device similar to the channel simulator, but with much greater flexibility in object placement and pattern (characteristic) sequences is envisioned. In addition to providing fundamental psychphysical data, the experiments will give insight to patterns which facilitate positive identification.

III.D.1.3 Scope of Model Elements. A human factors model will be developed for detection and identification. In the preliminary model, variations in detectable range were accommodated by limiting the aids available to the observer, and correct orientation of the mariner was assumed. However, the Phase II model will permit evaluation of the interval required for detection and subsequent identification before information from an aid is used, as well as the probability of incorrect identification. Intuitively, the problem of identification would seem to diminish with orientation. Hence the probability of incorrect identification would be influenced by the mariner's confidence in his navigation parameters.

The elements of the model for detection and identification will include visual detection for day and night conditions, radar detection, visual identification for day and night conditions and radar identification for conventional PPI displays and for integrated navigation systems. Initial conditions will include a position uncertainty factor. Characterization of visual and radar patterns will be stratified to cover the range of identification problems derived by analysis and experimentation.

III.D.2 Traffic Facilitation

III.D.2.1 Proposed Index. A measure of traffic facilitation is required to assess the effect of system of aids to navigation on the efficiency of ship and port facility operations.

Factors which contribute to traffic facilitation include harbor improvements (e.g., widening of channels) and vessel traffic services, as well as aids to navigation. Since we are concerned with the evaluation of aids to navigation, the proposed index is limited to that contribution.

There are two parts to the problem—the availability of the harbor for use by a given class of vessel and, for those times that it is available, the transit time required. The proposed traffic facilitation index is the product of two factors, an availability index and a transit time index.

III.D.2.2 Availability Index. The availability index will be the ratio A_i/A_o, where A_o is the number of hours per base period (say, one year) in which a vessel of the type under consideration could safely transit a harbor segment if the mariner had perfect knowledge of the navigation parameters, and A_i is the number of hours per base period in which the same vessel type could safely transit the segment using only the information provided by the system of aids to navigation. The indices for a particular segment may be derived for a single vessel type or may be expressed as a weighted average for several vessel types of interest.

A_o will be the duration of the base period, minus those intervals in which the height of the tide precludes safe passage of the vessel, or does not permit sufficient clearance to satisfy a minimum bottom clearance regulation. (For those periods when tidal height is adequate, intervals when combinations of wind and current preclude safe passage will also be subtracted.)

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A_i will be equal to A_o minus any other intervals in which safe transit, using navigation parameters derived from the system of aids under consideration, is not possible. To derive A_o, it will be necessary to apply the distribution of tides and currents, the correlations of which are usually well known, and of wind. The highly aggregated meteorological data that are readily available for most areas will not usually permit the derivation of correlation factors for wind and current. However, in most areas winds can be treated as an independent variable (allowances will have to be made for those bodies of water in which wind-driven currents significantly modify tidal effects). In addition, the computation of A_i will require the distributions of brightness (a trivial task) and visibility conditions, and where applicable, their correlation factors. Preliminary efforts may treat the correlation of brightness with any other ambient condition as random (this neglects the sea breeze and land breeze effects). In many areas, fog or haze-caused low visibility will correlate with wind conditions and brightness.

III.D.2.3 Transit Time Index. The transit time index is the ratio t_i/t_o, where t_o is the time required for transit of the segment with perfect knowledge of all pertinent navigational parameters and t_i is that required for transit with the information derived from the system of aids to navigation.

There are two factors which may affect transit time under those conditions when safe transit is possible:

- With perfect knowledge of his navigation parameters, the mariner would follow an ideal track which provided the desired margin of safety, and which therefore represented the shortest route without sacrifice in safety. With less than perfect knowledge, the vessel would deviate from that track somewhat, or a modified track providing larger margins to compensate for uncertainties would be followed.

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- The speed at which a mariner would proceed through restricted waters may be influenced by his confidence in the navigation parameters.

In most harbors and waterways, it is apparent that the foregoing factors will be of small consequence. Relatively large deviations from the ideal track, within the confines of the waterway, would be unlikely to increase the track length by more than a few percent. In coastal navigation, or in the transit of broad waterways, the track length differences may be significant. The tendency of a mariner to reduce speed when he has less than perfect knowledge of his navigation parameters is postulated, but at this time is without basis for quantification. Future pilot interviews will be structured to acquire objective data.

III.D.2.4 Application of the Traffic Facilitation Index. Summaries of meteorological conditions for virtually all U.S. waters are readily available. These data are usually in the form of monthly averages and extreme values. They rarely provide any means to determine correlation. It is postulated that correlation factors of acceptable accuracy for those conditions which have the greatest effect on navigation could be derived from the summary data in conjunction with information from persons having extensive local knowledge. If for any reason it were necessary to develop more accurate, detailed data, hourly observations are usually available from NOAA on magnetic tape.

III.D.3 Buoy Stationing Error

III.D.3.1 The Stationing Problem. In a harbor segment marked with buoys, the view seen by the navigator will be somewhat different from that represented on the chart. The displacement of a buoy from its charted station due to its scope of chain and the survey error in placing its anchor is likely to be relatively small. However, the effect of the displacement will impact the navigators estimate of his navigation parameters. Further, there is the possibility of gross displacement through dragging.

The Phase I effort concentrated on the ability to determine navigation parameters from "perfect" patterns. Extension of the human factors models to include error functions for the information derived from imperfect patterns is required. Information derived from this data will indicate the relative worth of more accurate placement or of fixed rather than floating aids.

All standard navigational texts caution mariners on the reliance that can be placed on buoys, and interviews with pilots indicate that they regularly confirm correct stationing by comparison with fixed objects whenever possible. However, there is no quantitative data on the ability to detect stationing errors as a function of magnitude.

III.D.3.2 Sequence of Analysis Steps. *Acquisition of Basic Data*. The initial step will be an analysis of the patterns seen by the navigator and the development of hypothesis to quantify the effect of stationing error on the information derived from the patterns. The variables to be treated include the "size" of the pattern (e.g., number of buoys), the availability and relative placement of fixed aids, the magnitude of the stationing errors and the navigation parameters of primary interest to the mariner. Two classes of error will be treated;

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those due to survey error and scope, and gross errors due to dragging. The distribution of survey errors will probably be gaussian, and will be applied randomly to each buoy. Scope errors will vary in magnitude with tidal height and may be random in their direction vector (slack water) or biased (significant current). Further study is needed to characterize errors due to dragging. Very large errors would most likely be the equivalent of removal of the buoy if the context and visibility made the displacement obvious. Large displacements of several buoys in a pattern could result in complete misinterpretation unless other aids or objects were available for correlation.

The pilot interviews during Phase I indicated that large displacement of several buoys in a pattern was not uncommon. It is possible that the pilot had been sensitized to this condition by the severe ice conditions of the preceding winter. In any event, the investigation will include multiple displacements of substantial magnitude even though it may be subsequently determined to be an unrealistic modeling factor.

Human Factors Experiments. A mock-up will be designed to simulate stationing errors in buoy patterns and experiments will be conducted in our human factors laboratory to acquire data on the changes in information that result from stationing errors. The data will be directly usable in the model, but will be treated as testable hypotheses until checked by simulator trials or ship trials. This last step is important since the data derived from the human factors experiments will not reflect the influence of external factors.

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Thus, the analyses to be conducted in Phase II under this investigation are:

- Relate the degree to which buoys may be off-station to the ability to recognize and use patterns for navigation.
- Estimate the effects on the error maps for the navigation scenarios of buoys being off station.

Once the effects of buoys being off station is reflected in the error maps, the effects on the navigation process can be easily determined though the navigation models previously discussed (e.g., run and observe model). The sequence of analysis steps are:

- Postulate the effect on the information available to the mariner from the A/N system when buoys are off-station.
- Conduct experiments in the Human Factors Laboratory to simulate changes in the information available due to buoys being off-station.
- Analyze the data and formulate testable hypotheses that can be checked by simulator trials. Verification of the testable hypotheses by simulator trials would tend to support the models developed for reflecting the effects of buoys being off-station in the error maps.

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GLOSSARY

cross-track location. The distance between a vessel's center of gravity and a reference line, measured along a line normal to the reference line (or normal to a tangent to a curved reference line). The reference line may be a channel axis, channel edge or an ideal track. In the latter case, the cross-track location is equal to cross-track error.

grounding constraint. Physical limitations or legislated requirements which restrict a vessel's movement.

grounding contour. The boundary of the grounding domain, which separates the grounding and safe domains.

grounding domain. Values of the navigation variables that cause the vessel to go aground.

leading light. A light positioned on the axis of a channel, some distance beyond the end of the channel, so that a navigator will attempt to travel directly toward the light.

navigation variables. Measurable components of the ship's position and movement, defined with respect to a specific grounding constraint, that can be used to predict that the vessel will ground.

observables. The physical characteristics of objects, or of the relationships between objects, that permit the extraction of navigationally relevant information. Suppose, for example, that a navigator wishes to know his distance from the right side of a channel. If he obtains it by estimating the distance to a buoy abeam, then distance to the buoy is being used as an observable. If he obtains it by noting the amount of split between buoys marking the channel edge, then the visual angles separating those buoys are being used as observables.

probability contour. The true values of the navigation variables lie within a probability contour with a specified level of confidence. For example, the probability that the true values of the navigation variables lie within the 90 percent probability contour is 0.9.

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psychological scaling. The process of using a human being as a measuring instrument. Objects or events may be measured with respect to purely psychological characteristics such as beauty, prestige, etc.; or they may be measured with respect to psychological correlates of physical characteristics such as loudness (correlated with sound intensity) and apparent length (correlated with physical length).

psychophysics. The study of psychological scaling of quantifiable physical stimuli such as size, loudness, and brightness; also concerned with minimum detectable stimuli, such as the softest sound that can be heard, and minimum detectable differences between stimuli, such as the amount by which a length must be increased before it is noticed as being longer.

range of opportunity. Any two objects, other than range lights or range marks, used as a range.

reference point. In psychological scaling, an object or event which is used as a standard. Other objects or events are assigned values by comparing them with one or more reference points. Reference points are often the endpoints of a psychological scale. Values near reference points are assigned more consistently (i.e., the scaling process is less subject to error) than are values farther removed from reference points.

run and fix. Same as run and observe.

run and observe. The process of inferring direction of motion by making successive observations of cross-track location. Explicit run and observe refers to making observations at planned points of advance, a known distance apart, so that direction of motion can be explicitly calculated. Implicit run and observe refers to a correction process whereby a navigator proceeds until he notices that his cross-track location has changed, then changes course to return to his desired position.

safe domain. Values of the navigation variables that are not in the grounding domain.

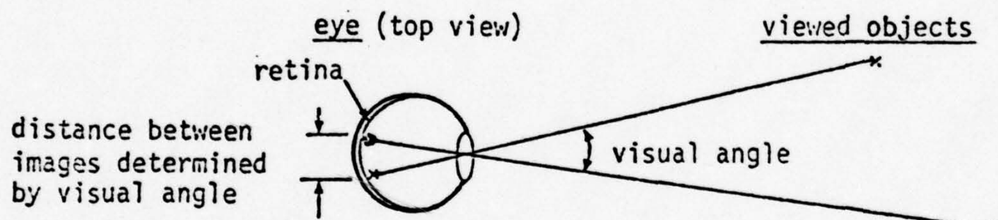
signal detection theory. A mathematical formulation, adopted by psychophysics from communication theory, which permits separation of errors caused by the variability of human sensory systems from errors caused by response biases (e.g., a tendency to say "different" when in doubt about whether two stimuli were in fact different).

slope. The ratio of the vertical component to the horizontal component of a visual angle.

swing. The apparent motion of the bow of a turning vessel with respect to a fixed object.

threshold. The minimum stimulus that is detectable (absolute threshold), or the minimum difference between stimuli that renders them detectably different (differential threshold). In this context, "detectable" generally means detected fifty percent of the time.

visual angle. The angle formed at the eye by straight lines extending from the eye to the edges of an object; see diagram. The size of the object's image, as projected on the back of the eye by the eye's optics, is determined entirely by visual angle. Visual angle is therefore used by psychologists as the measure of that image size.



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BASIC ANALYTIC TECHNIQUE FOR
DESIGN & EVALUATION OF SYSTEMS OF
AIDS TO NAVIGATION

APPENDIX A
HUMAN FACTORS ANALYSIS

JULY 1978

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APPENDIX A

HUMAN FACTORS ANALYSIS

I. INTRODUCTION

This Appendix contains materials which serve as the basis for statements made in the body of the technical report. Included are illustrative figures; tables and notes from interviews with pilots; internal memoranda; and a report on the range sensitivity experiment conducted under this contract. To assist the reader in using those supportive materials, a summary is presented below which describes the connection between conclusions reached and the evidence on which those conclusions are based. In some cases, hypotheses are discussed which, because rejected, are not mentioned in the body of the technical report. It is assumed throughout this Appendix that the reader is familiar with the concepts of observable, reference point, and visual angle, as used in the body of the technical report.

II. SUMMARY OF RATIONALE FOR CONCLUSIONS

II.A. Estimating Cross-Track Location in a Straight Channel

II.A.1 Center of Channel

Three lines of evidence indicate that the center of the channel should be a reference point, at least when the channel is marked with gated buoys. Perceptual analysis argues that the center should be particularly easy to identify because of the symmetry of the perspective view obtained from the center. As standard introductory psychology textbooks point out, symmetrical patterns are "good" figures in Gestalt perceptual theory. An early informal experiment showed reduced error in estimating location when at the center of the channel than when between the center and the edge. The results of that experiment were essentially duplicated by a more recent experiment using a channel perspective simulator. (The experiment is

described in a March 22 memo; see page 76. A description of the simulator appears on page 78.) Pilot interviews indicated a preference for the center of the channel, although the reasons given were not always related to ease of telling where they were (Table A-7, page 40).

Two observables have been identified which are associated with a reference point at the center of the channel. The first applies only to a channel marked with gated buoys. The mariner is assumed to determine his position by comparing the visual angle separating two port buoys to the visual angle separating the corresponding starboard buoys. The observable is taken to be the ratio of those two visual angles. Psychophysics consultant John Baird judges the ratio to be the appropriate comparison, and he was able to provide information permitting quantification of error as

$$\sigma_R = (.5|\log R| + .1)R$$

where σ_R is the standard deviation of judgments of ratio R. (A discussion of the derivation of this equation is contained in a January 17 memo; see page 73.)

The salience of the angle-ratio observable was supported by pilot interviews. When shown diagrams with most of the perspective distance cues removed, pilots were able to identify themselves as being in the center of the channel with a gated-buoy diagram (Table A-3, page 34), but not with a staggered-buoy diagram (Table A-6, page 38). While the inability to locate themselves in the staggered-buoy diagram is suspect because of the loss of depth cues, the contrast between gated- and staggered-buoy diagrams suggests the sufficiency of the angle-ratio observable. Furthermore, some pilots clearly indicated the equality of visual angles as the basis for their judgment of location (Table A-3, page 34).

Our analysis originally included only angle ratio as an observable producing a reference point at the center of the channel. Consequently we predicted that error would not be reduced at the

center if the channel were marked with staggered buoys. We regarded the question as one of model validation. However, analysis of the edge of the channel eventually led to evidence that the slope of the line connecting the buoys, as projected onto a plane perpendicular to the line of sight, was an observable for a reference point at the edge of the channel; see Section II.A.2. This led us to hypothesize that a second observable is available which creates a center-of-channel reference point. That second observable is one relating to the comparison of the slopes of the lines along the two sides of the channel. While we have not characterized the slope comparison process mathematically, we assume that equality (mirror image) will be easier to judge than any other relationship. Preliminary experimentation (March 22 memo, page 76) supports the existence of a center-of-channel reference point for staggered buoys.

Since there is evidence for the salience of visual angle ratio as an observable, it is likely that the observable associated with slope comparison supplements rather than replaces angle ratio. There is some suggestion in the data from the informal experiment just cited that the two observables together provide lower error at the exact center of the channel than does slope comparison alone: Error was lower for gated than for staggered buoys at that location by a fairly substantial amount that was not, however, statistically significant [$F(9,9) = 2.99$; significance at .05 level of confidence requires $F = 3.18$]. It will be necessary to characterize slope comparison as an observable, and to perform careful experiments to measure the relative contributions of the two center-of-channel observables.

II.A.2 Edge of Channel

Two observables have been identified which have the edge of the channel as a reference point. One is only intermittently available, being associated with having a buoy abeam. The other is available whenever the channel edge is marked.

Early analysis identified the edge of the channel as a reference point because, from that location, the buoys along the edge would be on range. Ranging has been studied fairly extensively (Arnold & Woodward, 1977), and it is performed quite precisely. However, for ranging to provide an observable consistent with our analysis, it is necessary that mariners be able to use ranges to hold an off range position as well as to maintain a position on range. Furthermore, error should be greater for staying off range than for staying on, if the on range position is to serve as a reference point.

Interviews with pilots have consistently indicated their ability to use ranges to stay off range (Table A-2, page 33; Table A-27, page 71). Thus ranging appears to be an appropriate way to describe the task of staying away from the edge of the channel.

There are at least three potential observables associated with ranging. The most obvious one is suggested by the description of a range as "split", and that is the horizontal component of the visual angle separating the two objects being ranged. The second one can occur only if the relative distances of the ranged objects can be judged. It was suggested to us by our own intuitive reactions in looking at photographs of navigation scenes: We had a strong sense of a line through the buoys extending back past the ship, and we argued that the mariner could follow that imaginary line back and estimate its distance from a point abeam. The third potential observable was suggested by our attempts to describe imaginary lines: The slope of the line through a set of buoys is constant for a given distance from a channel edge, regardless of distance to the nearest buoy and regardless of buoy spacing; hence, we suggested slope as an observable.

Interviews with Delaware River pilots suggested that distance is not estimated to a point on a line mentally drawn through the

buoys and extended abeam. While some of our respondents reported using lines, all reported making their judgments strictly by looking ahead (Table A-27, page 72). That left us with the slope and horizontal-visual-angle hypotheses.

An experiment was performed to select between slope and horizontal visual angle as the observable for edge of channel ranging, and to measure the error associated with that observable. Because of the difficulties associated with experimenting with off-range rather than with on-range positions (see Arnold & Woodward, 1977), we designed the experiment in accordance with signal detection theory. Section III considers that and other aspects of the design with respect to the applicability of the experiment to our modeling effort. The experiment itself is described in a report beginning on page 79.

The experiment produced two error equations for the observable associated with ranging. Expressed as changes in slope, the standard deviation is a linear function of slope (S):

$$\sigma_S = .05390\ S + .01518$$

Expressed as changes in horizontal separation, the standard deviation is a function of both horizontal (H) and vertical (V) separation:

$$\sigma_H = .05341\ H + .01003\ V + .21142$$

when H and V are expressed in minutes of arc. The expression in terms of slope is simpler, and it was shown that if slope was used to predict error expressed as changes in slope, no significant improvement in prediction could be obtained by describing the observable in other terms.

Based on those results, we regard slope as the appropriate way of describing the observable associated with the openness of a range. The error equation is based on optimal conditions and should probably be adjusted in the manner suggested by Baird for visual angle ratios (January 17 memo, page 73).

As noted at the beginning of this section, a second observable is available when there is a buoy directly abeam. The Sandy Hook pilots were particularly clear about their practice of directly estimating distance off such buoys (Table A-5, page 37). There are three commonly-available observables for direct distance estimation. When an object is far away, it subtends a smaller visual angle than when it is close (Figure 1-A); when it is far, the visual angle subtended by the distance itself is larger than when it is close (Figure 1-B); and when it is far, the visual angle between the object and the horizon is smaller than when it is close (Figure 1-B). The first potential observable is fairly well studied, and based on it we have modeled the standard deviation of error in estimating distance (D) as

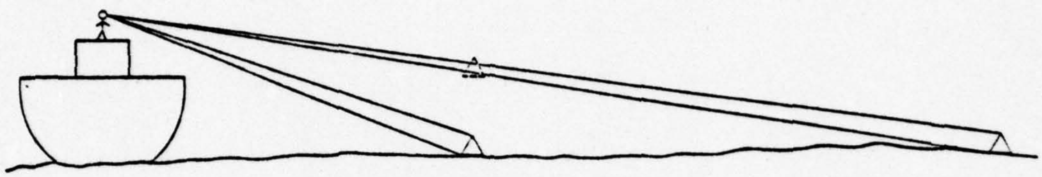
$$\sigma_D = .1D$$

Unfortunately, distance tends to be overestimated when the visual angle subtended by an object is used as an observable, but it tends to be underestimated over water. There is some indication from the Delaware River pilots that the second observable (visual angle subtended by the distance itself) is used (Table A-27, page 69). We note that that observable is inherently confounded with the third in practice. According to our psychophysics consultant John Baird, estimation of distance based on the distance itself is the least well studied of all aspects of visual space. Experimental work is needed in this area.

II.A.3 Ranges

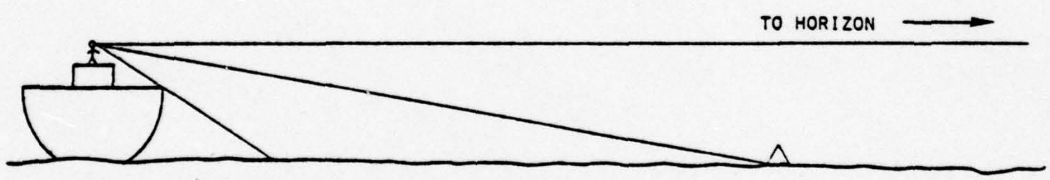
Any on-range position is a reference point. Since the edge of channel (with no buoy abeam) was studied in terms of ranging, we expect most of the analysis reported for the slope observable to be applicable to ranges. There are two fairly clear exceptions. First, since the two parts of a range are not generally in a plane parallel to the plane of motion, the slope does not remain constant for a given distance off range, but rather it depends on the distance

A.



VISUAL ANGLE OF OBJECT OF KNOWN SIZE

B.



VISUAL ANGLE OF EXTENT OF WATER, OR OF DIP

FIGURE 1. POSSIBLE OBSERVABLES FOR DISTANCE ESTIMATION.

from the range. Therefore an unfamiliar range cannot be used to establish an off range position,as pilots have indicated (Table A-2, page 33). Second, when a range is very nearly closed, a person familiar with it may be able to use supplementary information. For example, rather than establish a particular slope, he may align the left edge of the upper daymark with the right edge of the third stripe on the lower one. In other words, the range may be redefined to produce a new on-range position.

II.B. Estimating Direction of Motion in a Straight Channel

II.B.1 Direct Sensation of Lateral Motion

Pilots report that it is sometimes possible to get a direct sensation of lateral motion. Lateral motion is easier to detect from points near the edge of the channel, and it is easier to detect at low forward speeds (Table A-8, page 41). It is comparatively difficult to judge from the motion of a single object relative to the ship, and is more easily seen in terms of ranges of opportunity, or in terms of the motion perspective of a buoy seen against a background (Table A-27, page 69).

As noted in the body of the technical report, the observables associated with direct sensation of lateral motion have been only tentatively identified. What is required is that objects change bearing in an incorrect manner (e.g., too slowly or too rapidly). Incorrect changes are most clearly definable when an object changes bearing forward (Figure 2-A) or when a range to one side opens in the wrong direction (Figure 2-B). Hence we propose these observables for direct lateral motion detection.

The interview data cited above indicate that the observables used are only sometimes salient. Just when they may be expected to have an effect is uncertain, since studies on motion detection (e.g. Harvey & Michon, 1974) are concerned with motion of objects toward or away from each other, whereas changes in bearing and opening of

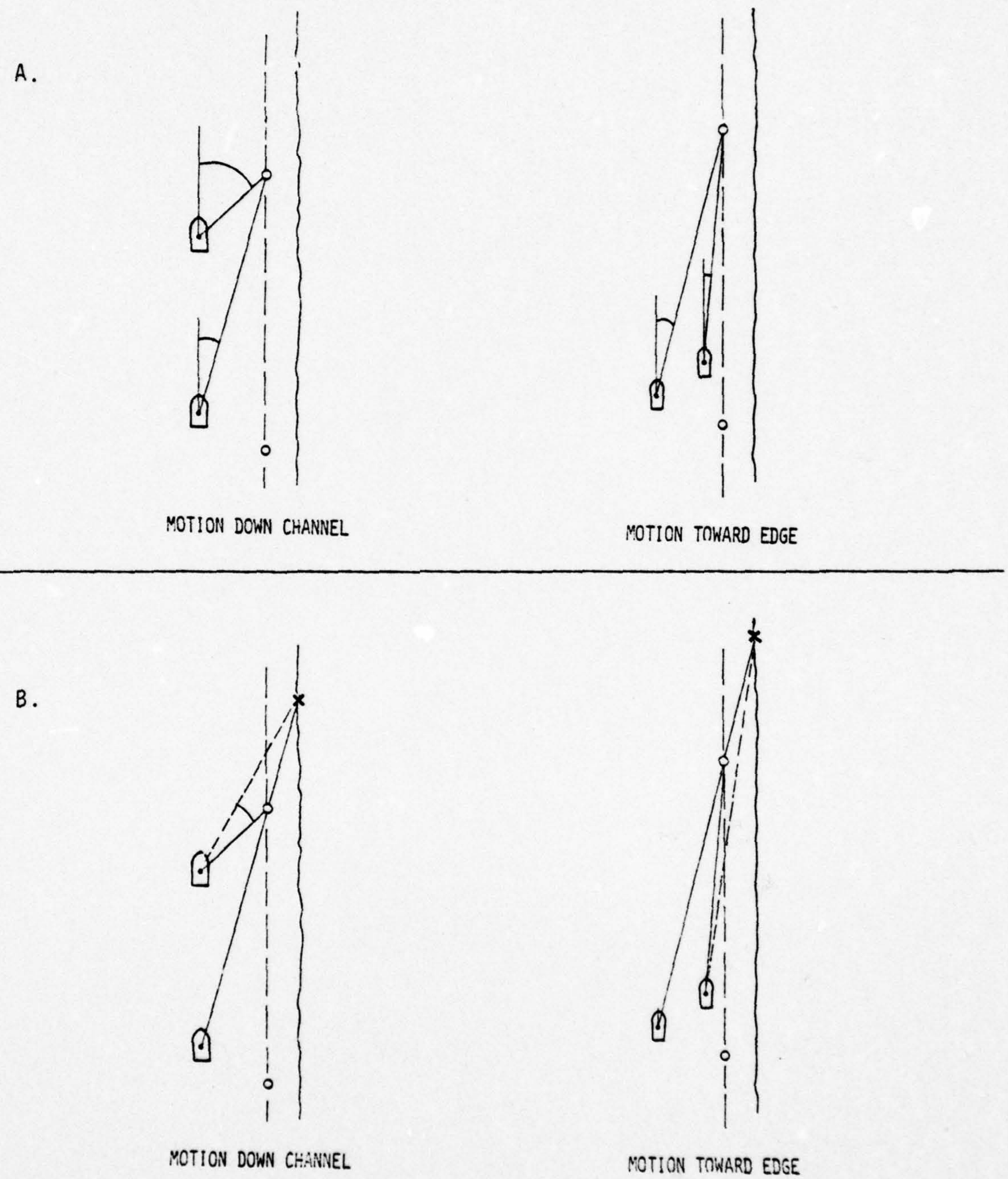


FIGURE 2. LATERAL MOTION CAUSES INCORRECT DIRECTION OF CHANGE OF BEARING (A) AND CAUSES RANGED OBJECTS TO OPEN IN THE WRONG DIRECTION (B).

ranges are motions of one object past another. We therefore expect experimentation to be necessary, both to determine what size of lateral motion is necessary before direct sensation of it has an influence, and to determine whether our choice of observables is correct. In any case, we would expect direct sensation of motion to apply limits on the directions possible in an implicit run-and-observe process (see Section II.B.2), rather than to provide actual estimates of direction of motion.

II.B.2 Run and Observe

Most of the time, direction of motion does not appear to be directly estimated or even directly sensed. Rather, direction of motion is the result of correcting changes in cross-track location. One detects whether one's direction is correct by observing cross track location, running down the channel, and again observing location. Lateral drift that is too slow to be detected directly can thus be noticed, just as one can notice that the hands of a clock have moved, even though one cannot see them moving.

Run and observe detection can be used for explicitly estimating direction of motion. Sandy Hook pilots commonly referred to the formula 100 feet in one mile is one degree, and they spoke of checking lateral drift at fixed mile or half-mile intervals (Table A-8, page 41). Such explicit run and observe estimation cannot cover all cases, and it seemed quite uncommon among Delaware River pilots. These latter reported progressing until they felt uncomfortably far off, then moving back to their desired track and resetting their course. The corrected course was set by trial and error, not by adjusting for a computed error in the previous course (Table A-27, page 70).

The implicit run and observe procedure reported by the Delaware River pilots, in which direction is simply a byproduct of corrections in cross-track location, seems to us to be a basic pro-

cess. It is the only process that can handle slow drift when buoys are not frequently available to indicate distance of advance. Explicit run and observe seems to be a special case in which the course set is less random than it is with the implicit process. Direct sensation of lateral motion merely places limits on the extremes; in setting a new course once position has been corrected, one will certainly not make an error large enough to result in immediately detectable drift.

In modeling the run and observe procedure, we have employed a control theory model. That model produces gradual improvement in position and motion as the channel is transited. Thus it seems to solve a considerable portion of the problem of harbor entry, since it takes length of time in channel into account. The model does require as input an initial distribution of positions and directions. Delaware River pilots indicate that they can set their direction within a couple of degrees, based on wind and current and without reference to A/N (Table A-27, page 70). Input positions are the portion of the channel entry problem yet to be solved.

The fact that direction is not estimated directly, but is a consequence of position correction, has raised some important questions for the model. The correction process depends on a navigator's strategies as well as on his perceptual skills. For example, the model requires that the ideal track not be a line, but have a specifiable width. Future treatment of the human factors of the model will have to deal with questions such as the specification of that width.

II.C. Negotiating a Bend

We hypothesize that a navigator approaches a bend with a particular rate of turn in mind, which he expects to achieve with a predetermined rudder command. The rate may be a matter of personal preference (Table A-17, page 50). But combined with an appropriate turn point, the rate determines a desired track around the bend.

The pilot's task then becomes threefold. He must begin the turn at the right point of advance; he must monitor the turn to make sure that actual rate of turn is appropriate to the actual turn point selected; and he must stop the turn when the ship is appropriately close to the course of the new channel leg.

II.C.1 Initiating a Turn

Three observables have been identified for initiating turns. Two are range type observables, and one is a distance observable. Sandy Hook pilots most commonly talked about the range formed by the inside turn buoy and the next ahead buoy (Table A-20, page 59), which marks the new edge of the new leg as a reference point. This observable was also mentioned by Delaware River pilots (Table A-27, page 68). Geometrical analysis shows that it has the advantage of being self-correcting. If the pilot plans to turn when the buoys are open by a specific amount, he will turn earlier if he is on the outside of the channel than if he is on the inside.

The second range type observable mentioned was the range on the new leg (Table A-20, page 59; Table A-18, page 54; Table A-27, page 68). This observable usually marks the center of the new leg as a reference point. It is cited for its stability. Buoys can drift off station, and the range can be used to check on the buoys, and can substitute for them if they are wrong.

The third observable is that associated with distance to the inside turn buoy. This observable is available even in limited visibility, and one pilot expressed a preference for it regardless of visibility (Table A-27, page 68).

Since the observables are of the same types as those identified for estimating cross-track location in a straight channel, selecting a turn point should involve no new principles. We did at one point explore the possibility that a dynamic cue (the point at which the inside turn buoy and the next ahead buoy

stop opening and start closing) was involved, but the variety of turn points required for different ships appears to preclude this possibility (Table A-27, page 68). We may find it necessary to adjust error formulas somewhat to allow for increased difficulty in picking the proper value of the observable when it is changing rapidly. However, the general shape of the relationship between error and distance from the reference point should be unaffected by any such adjustment.

II.C.2 Monitoring a Turn

We have identified three aspects of ship motion which are attended to once the turn has been initiated. They are the turning rate of the ship, change in cross-track location in the new channel leg, and change in cross-track location in the old channel leg. The observables used to monitor these aspects are only partially defined, and one observable may involve more than one aspect of motion.

It is quite clear that earliest attention is paid to "swing" - usually swing of the bow, but sometimes swing of the stern (Table A-22, page 61; Table A-27, page 68). The emphasis seems to be on an early cue to the adequacy of the turn rate. The observable is concerned with the relative motion of objects past the bow or stern. Objects seem to be anything, including wave patterns, within about 10° either side of the bow or stern. An alternative observable mentioned in the tables cited is the clicking of the gyrocompass repeater. Rapid clicking indicates a rapid turn.

Cross-track location in the new channel was emphasized heavily by the Delaware River pilots. As soon as the turn was initiated, these pilots reported giving their attention to the aids in the new leg. The rate of change seems to be important. The pilots are watching themselves decelerate across the new channel. If the turn is progressing properly, motion will stop when they are in the right

location. This task seems to be similar to a motorist deciding whether he is braking hard enough to avoid hitting the car stopped in the road ahead of him. The observables are presumably the same as for cross-track location in a straight channel; the only difference is that they are being used dynamically.

Cross-track location in the old channel leg was not explicitly referred to by pilots. It seems to be important only when the bend is sharp enough that significant lateral transfer takes place before the near edge of the new leg is crossed. The Sandy Hook pilots did report considerable attention to the inside turn buoy during the turn (Table A-21, page 60), in contrast to the Delaware River pilots. The usual cues for cross-track location are missing, since there is no line of buoys ahead (Section II.A.2) and since, with the ship turning, ship superstructure cues (Section II.E.) will be deceptive. The exact use being made of the inside turn buoy is unclear. John Kemp, our navigation consultant, has suggested that a constant bearing is maintained, and we have used that as an observable in our model. Actually, that observable integrates rate of turn, cross-track location in the old channel, and forward motion in the old channel, since all three affect it. However, for a turn that is progressing properly, the ships we have modeled hold the inside turn buoy at a fairly constant bearing for an extended period.

II.C.3 Stopping a Turn

Although stopping a turn is clearly thought of as a distinct operation (Table A-27, page 69; Table A-18, page 54; Table A-26, page 67), it does not seem to be a part of the turn at all from the point of view of modelling. The adequacy with which the turn is monitored and adjusted will determine the cross-track location when motion across the new track ceases. Some anticipatory action is required to make the swing stop at the same time, but by and large the turn seems to be stopped by leaving the turn-monitoring strategy and entering a straight-channel strategy on the new leg.

II.D. Night Navigation

Our analysis of visual A/N has been based on daytime visibility. The patterns that are produced by combinations of buoys are visible as patterns only if the individual buoys are all simultaneously visible. The condition of simultaneous visibility is not generally met at night. We were therefore concerned that nighttime navigation would require a completely new analysis.

Our concern appears not to have been well founded. Pilots indicate that they "see" the same patterns at night that they see in daylight - i.e., they remember the positions of buoys when they are dark, and they reconstruct the patterns. One pilot felt that the patterns were just as easy to use at night as in daylight, though others found them harder (Table A-27, page 71).

The informal experiment that compared gated and staggered buoys also compared patterns produced by continuously-visible and intermittently-visible buoys (see March 22 memo, page 76). In conformity with the pilots' comments, the results showed the same general relationship between cross-track position and error, regardless of whether the gated buoys were continuously visible. However, error was generally higher for the intermittent-visibility condition.

A complete analyses of nighttime navigation will require extensive examination of the effects of intermittent visibility. Although it appears that our daytime analysis will serve to identify the proper observables, the model should be able to predict the effects, not only of current patterns of intermittency, but also of possible alternative patterns. Consequently, investigation is needed into the process by which intermittent visibility has its effects.

II.E. Poor Visibility

Some pilots report using radar for navigation only when the visibility is quite poor (Table A-12, page 45). Consequently they

are sometimes navigating visually when very few aids are available ahead. Analysis in terms of visual angle ratios (Section II.A.1) and ranging (Section II.A.2) suggests that the ship's superstructure may be used in determining location when only one set of aids is visible ahead. When a buoy gate is visible, pilots apparently felt able to tell their cross-track location by relating that gate to the bow of the ship (Table A-1, page 31). If a single buoy is visible ahead, the ranging process is theoretically possible. Since the ship will be kept off range, and since the bow of the ship is moving, the slope between bow and buoy will not be constant for a given distance off range, and an estimate of distance to the buoy will be necessary. More complete information on strategy in such a situation will be required.

II.F. Electronic Aids

Much of the consideration of error associated with electronic aids has to do with the equipment itself, rather than with the user. We have, however, included some preliminary treatment of human factors error in using radar. A brief description of the current state of our analysis is included in this section.

II.F.1 Information Derived from a Radar Display

Using radar, the navigator may determine his position by measurement of ranges and bearings, or by direct visual observation of the over-all display. The pattern of the navigational aids is usually easy to recognize because it is a plan view of objects essentially as they appear on the chart. The Phase I model assumed that the navigator would estimate cross track position in a straight channel having its edges marked by aids by paralleling the mechanical cursor with the line(s) of aids, and estimating the cursor's position from the edge. When passing abeam of each aid, he would measure its range. When approaching a turn, he would measure the range to a fixed object to select a point to apply rudder.

Ignoring imperfect positioning of the aids to navigation, the principal sources of error are the inherent technical limitations of the radar (tolerances), adjustment and calibration, and operator interpretation. The first named category is usually small in radars of recent manufacture and may be ignored for most purposes. Imperfect adjustment and calibrations may result in an offset between the electrical and mechanical centers of the PPI display,lack of coincidence between the range marker and the time base, an offset between the bearing indicator and the gyrocompass, etc.. The most common causes of operator error result from improper alignment of the range marker and the cursor with the target when reading ranges and bearings.

When the operator estimates his position by direct visual interpretation of the display, the effects of range and bearing errors are of no consequence since his estimate is based on relative data.

For the phase I model the bearing error was assumed to be $\pm$ 1/2^{0}+ unknown compass error, and the range error to be 1% of range plus 1/2 the smallest increment of the range mark read-out. In addition, an error due to approximate conversion of slant range to horizontal range was applied for objects close aboard.

Errors in direct visual interpretation were based upon accepted factors for visual estimation of paralleling, interpolation, and distance scaling. The error in cross-track position derived from direct visual interpretation was assumed as $\pm$0.05 the channel width when both edges of the channel were marked with radar-detectable aids and as $\pm$0.1 of the distance from the marked edge when only one edge was marked.

II.F.2 Information Derived from Hyperbolic Radio Systems

Only LORAN C was treated in the phase I model, although virtually any hyperbolic system can be accomodated with the same technique.

There are two fundamental differences between the information received from LORAN C and that received by radar or visual means: the position data is presented in terms of coordinates (either hyperbolic or spherical, depending on the degree of sophistication of the receiver) rather than in relation to nearby objects, and the residual errors have a random characteristic. If the LORAN C receiver is interfaced with an integrated navigation system, the first mentioned difference can be eliminated. However, under such circumstances, the radar data would be available simultaneously and it is likely that the mariner would tend to rely on the radar position data.

For the phase I model, the "fixed" errors were assumed to be zero. Such errors are primarily attributable to survey errors, the difference between the true earth geometry and the elipsoid used in calculating the time delay hyperbolas, and inaccuracies in the calculated or estimated propogation velocities for overland portions of the transmission path. They can be virtually eliminated by survey or greatly reduced by noting the offset of a LORAN C fix from one taken simultaneously from well surveyed objects. It was postulated that a prudent navigator would not attempt to transit restricted waters using LORAN C exclusively unless the fixed errors were eliminated or compensated for.

Typical distributions of true difference errors resulting from instabilities in the transmitting system, receiving system, and atmosphere noise levels were input to the model and the error gradient for the specific site was calculated. At frequent intervals, a distribution of position errors was computed.

The phase I model computed the mean square radial error rather than the N-S and E-W components, but for a straight channel case the radial error was converted to a cross-track error. For specific waterways and station pairs, the N-S and E-W components of error will be used.

II.G. Other Navigation Scenarios

II.G.1 Coastal, Broad Waterway, and Landfall

Evidence provided by EASAMS is that coastal navigation is a relatively mechanistic process. Large errors can be tolerated, and navigational strategy involves plotting fixes on a chart. The observables are bearings of objects, as determined with instruments. The errors associated with taking bearings and plotting them have been catalogued by EASAMS, but not measured.

II.G.2 Harbor Entry

The problem of aligning a ship to a channel entrance does not appear to be appreciably different from the problem of turning into a new leg of a channel from a previous one. The chief difference is that, in the absence of the navigational constraints associated with being in a channel, the pilot can hold himself well off the channel entrance, so he need not worry about running over the first buoy on the near edge of the channel. There remains, however, a need to assess the ability to use single objects such as sea buoys for getting in appropriate range of the channel's aids.

II.G.3 Constrictions

Interview data indicate that the observables for approaching constrictions are of the same kinds as are used in traversing a straight channel. Pilots talk about the apparent size (visual angle) of bridge abutments, which are equal when the bridge is approached from the center, and they talk about ranging on lights on the bridge or on objects of opportunity (Table A-9, page 42). Thus constrictions appear to be primarily short sections of unusually narrow channel, subject to the same kinds of analysis we have applied to straight channels and channel bends.

II.G.4 Sinuous Channels

Interview data support the notion that a sinuous channel is treated as a series of independent bends (Table A-24, page 63;

Table A-25, page 66). Our analysis of negotiating a bend appears to require only the modification that, instead of stopping a turn by entering a straight channel mode, the pilot must stop it by initiating a new turn. While the knowledge of what rudder will produce what rate of turn will be different (because the ship is already swinging), the information extracted from the A/N should be the same.

III. EXPERIMENTAL DESIGN CONSIDERATIONS FOR THE RANGE SENSITIVITY EXPERIMENT

An experiment was run to measure the error associated with using openness of ranged objects as an observable for judging cross track location. An experimental report begins on page 79. The experiment was designed in accordance with accepted practices in psychological research. Two standard design features are of particular importance, both to the applicability of the experiment run and to the design of future experiments. One is the use of signal detection theory, which permitted standard deviations of error to be computed from accuracy scores in detecting the difference between two discrete stimuli; the other is the use of a small number of non-mariners as observers (experimental subjects).

III.A. Signal Detection Theory

Early work in perception attempted to measure thresholds - minimum detectable stimuli, or minimum detectable differences between stimuli. Actual experiments always showed such thresholds to be variable, and reported thresholds even for a single individual were always averages of many observations. Interpretations in terms of momentary fluctuations and experimental error could not account for differences observed using different methods. For example, thresholds were small but consistent when observers were required to state in which direction two stimuli differed; they were larger and quite variable when they were allowed to state that the stimuli did not differ.

Signal detection theory provided an alternative interpretation which accounted for discrepancies in earlier data, and that theory has become widely accepted in psychology. The basic premise of signal detection theory interpretations is that the perceptual process is inherently variable: A particular stimulus will not always give rise to the same sensation. That variability is usually attributed to inherent fluctuations in the firing of neurons in the sensory system.

When an observer is required to discriminate between two stimuli, the difference in perception caused by the difference in stimuli may be regarded as a signal. That signal is superimposed upon a background of noise, which is the inherent perceptual variability. If two stimuli are very similar, the difference between them may sometimes be obscured by the noise. Sometimes the lesser of two stimuli will give rise to a relatively large sensation, and sometimes the greater stimulus will give rise to a relatively small sensation; then the stimuli may be confused.

Our model is concerned with the perceptual variability, or error, associated with those stimuli used as observables. Essentially, then, we are interested in measuring the noise distribution described by signal detection theory.

The strategy for measuring noise is illustrated in Figure 3. Consider the lesser of two stimuli. That stimulus gives rise to a distribution of sensations, which are represented by the "N" distribution in Figure 3. The larger of the two stimuli will also have a distribution, but the distribution will be centered around a different point. The distance between the central points of the distributions represents the actual difference between the stimuli, which is the signal. The distribution about the higher central point is noise again, but it is noise associated with presentation of the signal; hence it is a signal-plus-noise (S + N) distribution.

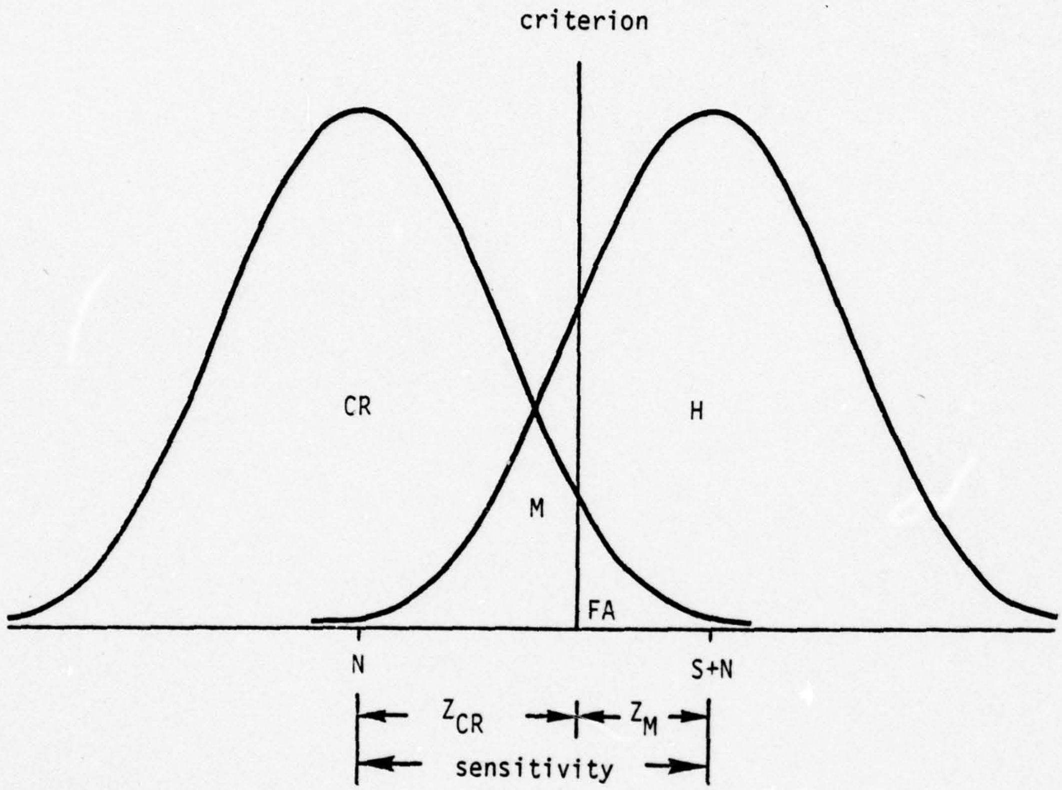


Figure 3. SIGNAL DETECTION DESCRIPTION OF PROCESS OF DISCRIMINATING BETWEEN TWO SIMILAR STIMULI. SMALLER STIMULUS PRODUCES NOISE (N) DISTRIBUTION, WITH CORRECT REJECTIONS (CR) BELOW AND FALSE ALARMS (FA) ABOVE THE CRITERION; LARGER STIMULUS PRODUCES SIGNAL-PLUS-NOISE (S+N) DISTRIBUTION WITH MISSES (M) BELOW AND HITS (H) ABOVE THE CRITERION.

The ability to discriminate between an observation from the N distribution and an observation from the S + N distribution depends on both the size of the signal and the spread of the distributions. An observer attempting to make such a discrimination is assumed to establish a criterion, represented by the vertical line in Figure 3. If the sensation is larger than that criterion, he will guess that the observation came from the S + N distribution; if not, he will guess that it came from the N distribution.

The errors that an observer makes will depend on two factors, his criterion and the overlap of the distributions. The overlap of the distributions, depending as it does on their spread, can be used to determine that spread. The problem,then, is to remove the effects of the unknown criterion.

The effects of the criterion can be removed if one knows the shapes and relative spread of the distributions. Because of the nature of the task (comparing two very similar stimuli), the spreads are approximately equal, and the shapes of the distributions should be identical. Although the distributions are generally skewed, the skewness is of an order that permits approximation by normal distributions with different variances at different locations. And since the stimuli are so close together, the near-equality of the variances permits close approximation to be obtained by assuming normal distributions of equal variance.

Given the normality assumption, it is possible by examining the proportions of errors to determine the distance of the criterion from the means of the S and S + N distributions. The relative numbers of hits (correct detection of the signal) and misses (failure to detect the signal) are uniquely associated with a standard score in the S + N distribution. Similarly, the relative numbers of false alarms (detection of the signal in its absence) and correct rejections (correctly deciding that the signal was absent) are uniquely associated with a standard score in the N distribution. Both standard

scores represent the location of the criterion within the distribution in question.

If the criterion is a standard deviations above the mean of the N distribution, and b standard deviations below the mean of the S + N distribution, then the two means are a + b standard deviations apart. The number a + b is called sensitivity in signal detection theory, and is customarily designated as d'.

The sensitivity measure gives the distance between the means of the two distributions in standard deviation units. But that distance is acually the size of the signal, as determined by the experimenter. That size is known in some physical unit (millimeters in the experiment reported). Hence, to determine the number of physical units (i.e., millimeters) in a standard deviation, one need only divide the physical size of the signal by the sensitivity.

In the manner described, a close estimate of the variability of the perceptual processes may be obtained without requiring the observer to make a series of settings of a pointer, or a series of verbal estimates of size. Either of those processes is subject to additional error. Signal detection analysis is intended to get at the basic error in perceptual processes, without regard to the decision or strategy errors that can contribute to other measures.

III.B. On the Use of Few Observers

Under the assumptions of signal detection theory, basic perceptual processes are being studied. Such processes should not be very different from one person to the next. Consequently, it is not surprising that psychophysical experiments are customarily performed using very few experimental subjects. If people are alike, then one observer will be typical of the group; there is no need to take a large sample and average the results. And running few observers has an advantage, in that they can be studied intensively. Large numbers of observations on a single observer result in precise measurement of his performance.

A second advantage of few observers is that they can be chosen carefully. Signal detection tasks, and many other psychophysical tasks, are tedious. And while signal detection analysis can be quite effective at separating effects of perceptual variability from effects of an observer's decision criterion, it cannot compensate for careless performance by an observer who does not take his task seriously.

The arguments in favor of few observers apply with equal force to the use of observers who are not members of the group one wishes to study. For example, we are interested in pilots' perception, but we studied a college student and two recent graduates, all psychology students. If the processes studied are basic to the human nervous system, then it does not matter that the people we studied are not pilots. It may even be an advantage, in that they are less likely than the pilots to question the relevance or importance of the experimental task. Their performance may be a good indicator of what a pilot is capable of, better perhaps than the performance a pilot was willing to turn in would be.

Obviously, the assumption that people are similar with respect to what we studied is of critical importance. For that reason, we designed the experiment to permit us to test the possibility that our three observers differed. Large differences would indicate the need to overcome the problems of testing pilots, problems which are not trivial, but which are not insurmountable either. Small differences would indicate that the results probably can be generalized, although we should still check our results against a pilot or two to make sure there aren't any gross differences.

As stated in the experimental report, small differences were found. Those differences were overall differences in variability across all conditions. The experiment was designed to permit us to look for condition-specific differences - a tendency for changes in openness to affect error differently for different people. Fairly sophisticated analysis is required to check that possibility, analysis

which was precluded by cost and time limitations. Although visual examination of the data shows no particular tendency for people to respond differently to different amounts of openness, we believe that careful analysis should precede decisions about the design of future experiments.

III.C. Perceptual Variability and Performance

In Section III.A., it was mentioned that signal detection tasks exclude sources of error associated with motor operations and strategies of estimation. It may be questioned whether the exclusion of those error components is desirable. It is the case that signal detection experiments will indicate the best performance possible, rather than typical performance.

We believe that there is no advantage to confounding perceptual error with other sources of error in our experiments. Those additional sources of error may be typical of particular situations, rather than of navigation generally, even in experiments which successfully simulate some aspect of navigation. Rather than compound sources of error, we believe that we should study each separately, with attention to factors which determine when each is operative. Our first study is on perceptual error, because that is basic. The perceptual system places an absolute limit on the precision with which A/N can be used. We would expect there to be a multiplying factor representing the noisiness of the ship environment relative to the laboratory; once specified, such a factor should apply to laboratory results on many perceptual abilities. And we would expect there to be task- and choice-dependent factors, such as the criterion for specifying the width of a band of indifference: these, too, should be studied separately, so that they can be assigned their proper role in the model.

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STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS-PHASE I.--ETC(U)

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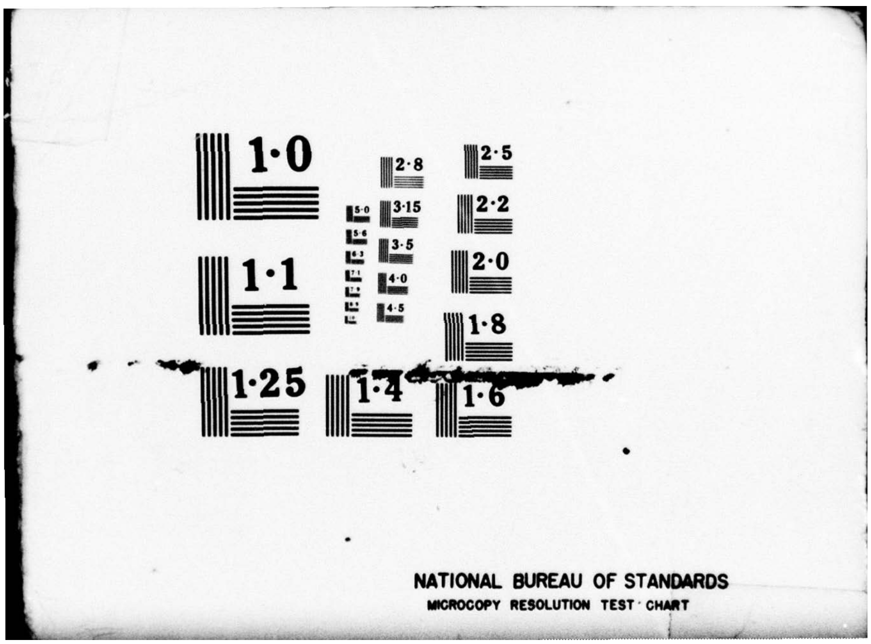
NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

REFERENCES

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Harvey, L.O., Jr., & Michon, J.A. Detectability of relative motion as a function of exposure duration, angular separation, and background. Journal of Experimental Psychology, 1974, 103, 317 - 325.

EXHIBITS

TABLES A-1 TO A-26. INTERVIEW DATA FROM SANDY HOOK PILOTS

On November 17 and 18 interviews were conducted with six members of the United New Jersey Sandy Hook Pilots Association. The interviews were tape recorded with the understanding that while excerpts might be published, the tapes and transcripts would be for the use of the interviewers only, as a substitute for written notes.

The interviews were organized around information objectives. For each objective the interviewer had a written set of prompts or suggested questions; in many cases the prompts were keyed to a visual stimulus card (such as a perspective drawing of buoys). Although organized around objectives, the interviews were not rigidly structured. Pilots were encouraged to talk freely in response to a stimulus card or a general question, and prompts were freely omitted if the desired information had been previously volunteered, or elicited by an earlier prompt. Consequently, the data presented here are not organized as responses to questions. Rather, they are organized as statements about points of interest to the interviewers, extracted from wherever in the interview they may have occurred. When possible data are presented in tabular form. In those cases requiring longer extracts to convey pilots' meaning, tabular presentation is replaced with a simple listing of quotations.

Tables A-1 to A-6 reflect responses made in the presence of, or relevant to, stimulus cards; the corresponding stimuli are indicated in the titles of the tables. The location column of those six tables represent apparent location, given that the stimulus card is a diagram representing what is seen ahead. The location column of the A-7, by contrast, represents preferred location.

Tables A-8 to A-16 represent responses to exploratory questions. The

notation NO RECORD in some of these tables indicates responses that were on a tape lost when the tape recorder in which it was mounted was stolen from the interviewer's desk.

Lists of quotations are presented in Tables A-17 to A-26. These quotations concern the processes of negotiating a bend and negotiating a sinuous channel. When necessary for ease in understanding, the prompts, questions, and comments of the interviewer are presented in parentheses. The large black dots to the left of the quotations indicate the beginning of each pilot's comments. In several tables there are less than six comments. This is due to the pilots' failure to answer the question asked (changing the subject) and to the mechanical failure of one recording. Due to the nature of the information being presented, it is believed that these quotations will give the reader more insight into the thought processes involved in negotiating bends in a channel than the tabular format would allow.

Stimuli are presented in Figures A-1 to A-11. Those which represent perspective diagrams are reduced in size from the cards actually shown to the pilots. The original diagrams were larger by a linear factor of 1.2 and were drawn on 5-by 8-inch cards, without boundary lines. They were viewed at a distance of approximately two feet.

TABLE A-1. CROSS TRACK LOCATION, ONE BUOY GATE IN VIEW (Stimulus 1)

Location	Cues used in determining location from card	Additional cues needed or normally used
1. Need more information		Pair astern, or bow of ship (suggested by interviewer).
2. Center of channel	Buoys are same distance from edge of card; can't tell how I know.	Next set of buoys; if badly off-channel, spread (visual angle) of buoys, assuming channel width known.
3. In the middle	Buoys are off each bow the same distance.	
4. (None stated)		Bow of ship, allowance for leeway, channel course; adjust perspective for size of buoys.
5. Center? ("Would move over to right" to be close to red buoy)	(Center location now suggested by interviewer) Buoys equal distance; bow of ship used; not so easy when wheelhouse is all the way forward. Height of buoys relative to (assumed) horizon.	
6. Perhaps slightly to left.	Height of buoys—"it's the only thing you've given me."	Could use structure on ship, if not crabbing. "I think you could do it" with 1° or 2° crabbing by using structure of ship. Just use direct distance estimation from observer's location.

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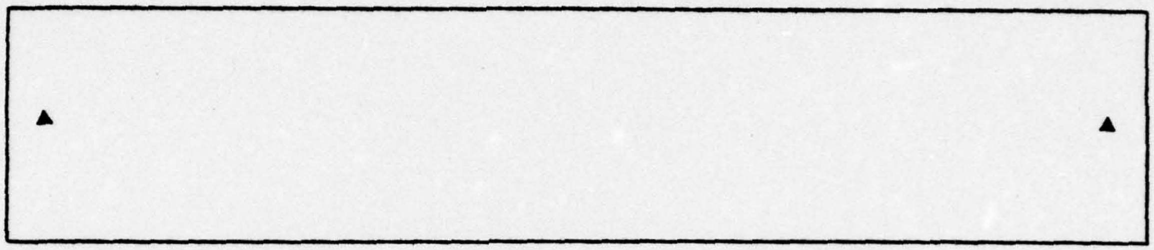

FIGURE A-1. STIMULUS 1—SINGLE BUOY GATE.

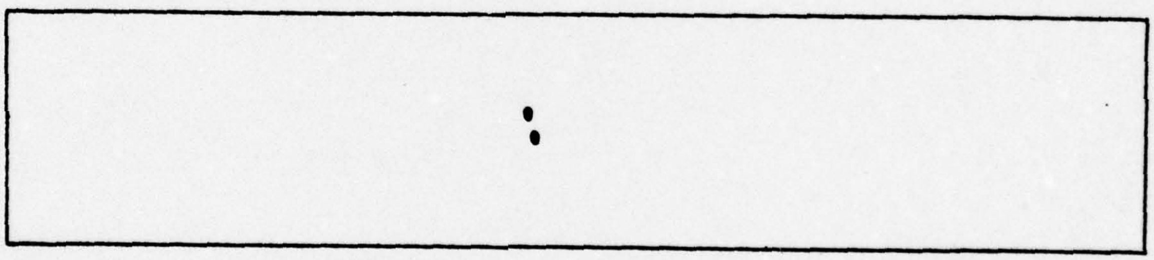

FIGURE A-2. STIMULUS 2—RANGE LIGHTS VIEWED FROM LEFT OF CHANNEL CENTER.

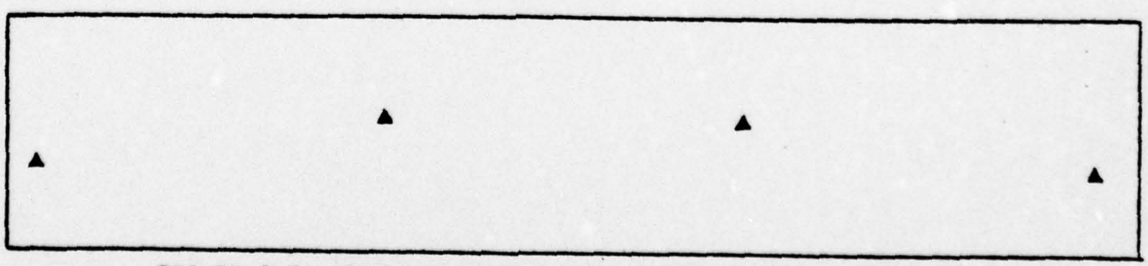

FIGURE A-3. STIMULUS 3—TWO BUOY GATES VIEWED FROM CENTER OF CHANNEL.

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TABLE A-2. USE OF RANGE LIGHTS TO MAINTAIN OFF-RANGE POSITION (Stimulus 2)

Evidence from identification of location	Evidence from selection of preferred location	Other evidence
1. "Slightly" left of middle, but distance unknown.	Would open up lights to exact opposite—need to know width of channel, distance from range.	Unirange not as accurate—you are either on or off.
2. Distance off unknown, but can decide whether too far.	Would open range slightly in wide channel.	
3. Could tell how far off if I'd been there before.		
4.	Can't tell how much to open lights unless you know range.	Ranges are "very effective" for keeping proper distance off and are normally used that way. Doesn't like unirange—"when they go from white to red you're already in trouble."
5.	If wanted to be on right, would crack range same amount the other way (familiar range assumed.)	Routinely use ranges to maintain distance off range. Can tell within scope of 200-300 ft. in Ambrose Channel.
6. 200 ft. to left in Ambrose Channel.		A familiar range is learned for different distances by looking at range and at distance off buoys.

TABLE A-3. CENTER vs SIDE LOCATION, TWO BUOY GATES VISIBLE (Stimuli 3 and 4)

Location, Stimulus 3	Location, Stimulus 4	Cues identified	Comparative ease of holding course
1. Roughly in the middle.	Right hand side—buoys will pass fairly close—1/3 on right.		Center easier for physical reasons, and requires less attention.
2. Center of channel.	Right side.	(In center) equal "distance" between two buoys on left and two buoys on right (i.e., equal visual angles).	Center easier for physical reasons—"could be" easy on side.
3. Right in middle.	Wrong side of channel.	(In center) funnel of channel. (On side, was assuming line of sight in center of stimulus card) something wrong with perspective.	
4. In center, absolutely.	Right side of channel.	(In center) splitting far pair of buoys.	Easiest place to stay is middle.
5. Probably to left—hard to tell, but you asked for a decision—very close (to center).	Closer to right side.	"Distance" (visual angles) between buoys on left and between buoys on right.	
6. About in middle.	Pretty well over on right hand side.	Opening and closing of buoys.	

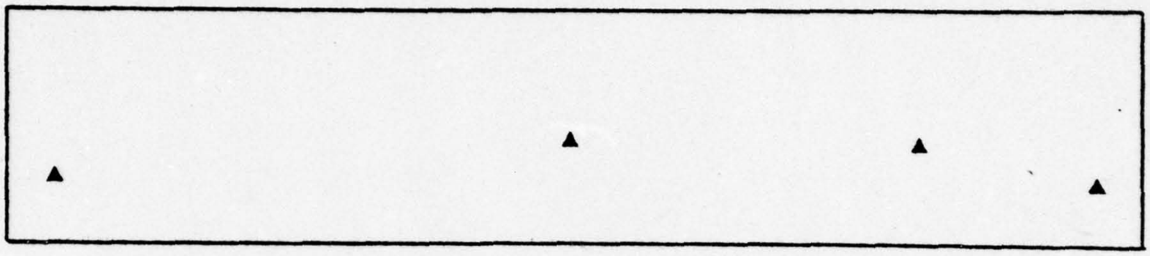

FIGURE A-4. STIMULUS 4—TWO BUOY GATES VIEWED FROM 1/3 CHANNEL WIDTH FROM RIGHT EDGE.

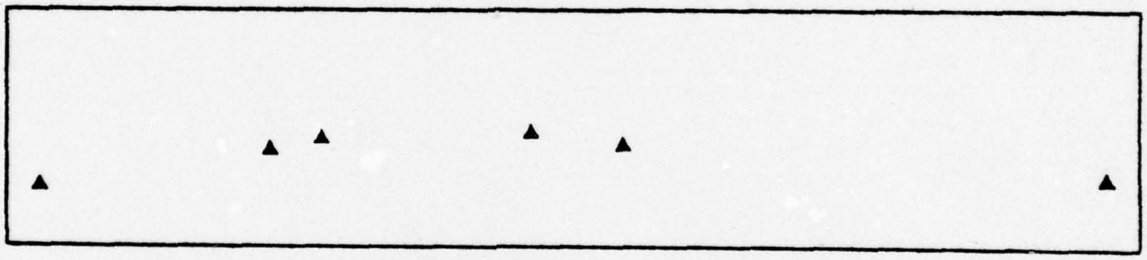

FIGURE A-5. STIMULUS 5—THREE BUOY GATES VIEWED FROM 1/3 CHANNEL WIDTH FROM LEFT EDGE; BUOYS MISALIGNED BY AMOUNTS REPRESENTING NORMAL SHIFTS WITHIN WATCH CIRCLES.

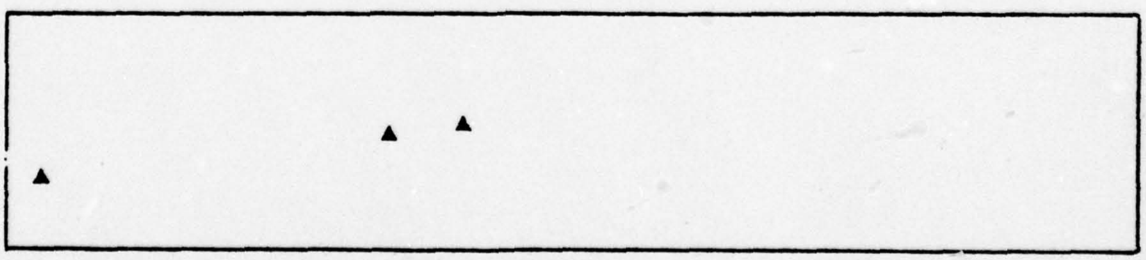

FIGURE A-6. STIMULUS 6—THREE BUOYS MARKING ONE SIDE OF CHANNEL, VIEWED FROM CENTER OF CHANNEL IF CHANNEL WIDTH AND SCALE ARE ASSUMED THE SAME AS FOR OTHER DIAGRAMS.

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TABLE A-4. DEFECTIVE ALIGNMENT, THREE BUOY GATES (Stimulus 5)

Location	Faults in diagram
1. Left side, 1/3 to left, maybe a little less.	Distant buoys not smaller than near buoys.
2. Left side, over a little bit.	"Something wrong" (when imperfect line-up pointed out).
3. Left side (after explanation by interviewer).	(Could not see perspective in diagrams other than center-of-channel.)
4. Left side.	None—deviations (when pointed out) are typical of buoys.
5. Left hand side.	Perspective should be narrower—depends on height of ship.
6. Wrong side of channel.	Buoys not as carefully gated as in other diagrams.

TABLE A-5. CROSS-TRACK LOCATION, CHANNEL MARKED ON ONE SIDE ONLY (Stimulus 6)

Location	Preferred location	Method of navigating	Remarks
1.	Go as close to buoys as safe.		Could judge distance if channel width known, but stay close.
2.		Keep buoys broken, especially more distant ones.	
3.		Buoy to buoy, estimating distance—don't want to see that (line of buoys ahead).	(Question not pursued, to avoid further problem with perspective diagrams.)
4. Would never see a split like that—on my way aground.	Near red buoys, 100-150 feet off.	When buoys ahead visible, don't have to worry so much about distance of buoy abeam, but still want to go out and check.	(Most of question answered spontaneously, before stimulus shown, assuming low visibility, when asked to define buoy to buoy navigation.)
5.		Split mentioned, but "I'm more impressed with that buoy abeam."	Looks ahead to see whether buoys on station.
6. Can't tell without buoys on right.	As close as possible to marked side.		

TABLE A-6. STAGGERED BUOYS
(Stimuli 7 and 8)

Location, 3 visible	Location, 4 visible	Remarks
1. Need more information.	A little to right side—would go closer to middle.	Wanted more buoys further ahead in three-visible situation.
2.	A little bit to the right side—a little too far to the right—would want to be in center.	With three visible, stay right of imaginary line between left-side buoys--go close to nearest buoy, back and forth across channel.
3. In the middle (?)—unclear whether perceived or desired position.	Coming down the middle.	
4. Right side.	Right side of middle—would hold my course.	With three visible, pilot continued to describe far two as pair, despite description of staggered buoy situation. No comments indicate whether problem persisted to four-visible situation.
5. On center line.	Can't tell—run for my chart, go to my radar, fathometer...	
6. To right.	Right side of middle. Continue as I am.	Did not appear to accept staggered buoy description of three-visible situation; felt buoy was missing with four visible.

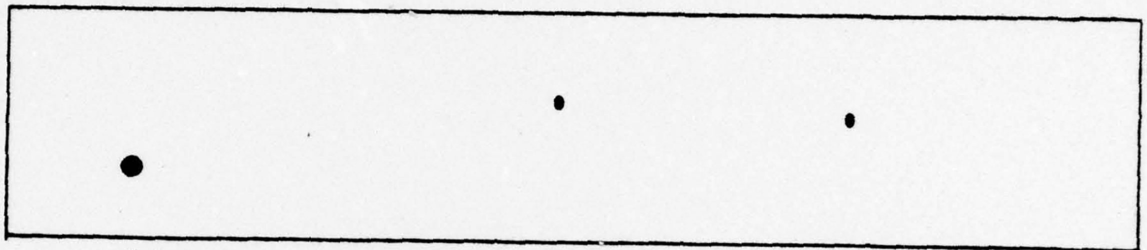

FIGURE A-7. STIMULUS 7—STAGGERED BUOYS, TWO PORT AND ONE STARBOARD, VIEWED FROM CENTER OF CHANNEL: DISTANCE BETWEEN PORTSIDE BUOYS IS TWICE DISTANCE BETWEEN BUOYS IN STIMULI 3-6.

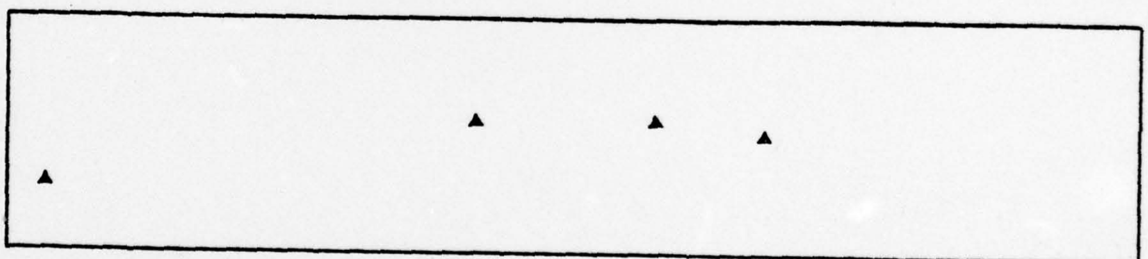

FIGURE A-8. STIMULUS 8—STAGGERED BUOYS, TWO ON EACH SIDE; SPACING IS THE SAME AS FOR STIMULUS 7.

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TABLE A-7. PREFERRED CHANNEL LOCATION

Location	Reason
1. Right of center.	Physically safer and requires less attention.
2. Center or just right of center, unless there is other traffic.	Center: safer, and easier because of physical reasons such as bank effects. Right: best situation legally if there is trouble.
3. Center "is mine" is there's no traffic.	Safest location.
4. Right of center except for very large ships.	Right of center is legally correct, and center is best maintained and less subject to shoaling.
5. Center or right side, depending on ship.	Safety implied: fast ships have less time-in-transit during which wind and current can move them, and maneuverable ships can be corrected easily. Slower, less maneuverable ships stay to center.
6. Right side of channel and close to middle (?).	(In response to question about using range lights to maintain position off center, position indicated was selected with comment "I'd be fine.")

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TABLE A-8. COMPUTATION AND SENSATION OF CROSS-TRACK MOTION

Computation methods	Direct sensation cues	Remarks
1. Note position every mile or ½ mile, at close approach of buoys.	Especially at slow speeds —ranged objectes opening.	Computation mentioned first.
2. If on range, go a mile; if off, you've drifted.		
3. Calculate distance off each buoy.	Watch movement by any stationary object ahead or close to bow.	Chose direct-sensation first—gave other when pressed to distinguish lateral motion from crabbing.
4. Judge course mile-for-mile; ranges very effective for this.	Can detect directly quite often-particularly when close, very close.	Reference to setting on top of buoy during turn, in discussing direct sensation.
5. (Pilot did not state computation method.)		Get "feel" of motion, as in setting course 5^o or 7^o off channel course because of feel that that's what you need, given that you're going slowly.
6. Judge course as each buoy is passed: "I don't see how else you could do it."		Indicated direct sensation under suggestive questioning, but referred back to successive location judgments when explaining.

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TABLE A-9 NEGOTIATING A DRAWBRIDGE

Strategy for Approach	Desirable aids	Remarks
1. Head toward middle.	Radar, compass, range; buoys (prompted by interviewer).	
2. Approach slowly to find center—most bridges have center lights—increase to half speed.	Lights on bridge to use as range; buoys, one on each side of bridge. Compass for benefit of helmsman.	Helpful to have straight course beyond bridge.
3. Watch movement of bow in relation to abutments—stay in middle.	Light over middle—usually available. Compass in foggy weather, and radar if lift lift bridge.	
4. Straight through unless turn follows bridge; on right side for right turn. Take away land equally on both sides to come straight through.	Low lighted range (range often available).	Ship steers better in middle of bridge. If visibility is so poor that A/N are needed, it's too dangerous to go through anyway. "Take away land" refers to amount of background visible, appearing past abutments as ship approaches.
5. Head toward side to open abutments like range—when begin to close, swing bow toward center.	Buoys desirable for wider bridges where height rather than width is critical.	Technique of "swinging through"is designed to keep rudder control, rather than relegating responsibility to helmsman by steering a course.
6. Use face of abutments to see how I'm lined up—I want to see how I'm lined up—I want to see equal amounts of the face of the opening.	Two lights on the face of each abutment, to open or close at night. Also buoy on entrance and on exit—anything to give structure.	Answers assumed going through center of bridge, which would be done when there was no tide or wind effect.

TABLE A-10. CUES MENTIONED FOR IDENTIFICATION OF BUOYS

	Color	Shape	Size	Number	Light color	Flash rate	Remarks
1.	✓	✓	✓		?	?	Comments on lighting unintelligible on tape.
2.	✓	✓	Yes (when prompted)	When close	✓		Red difficult in daylight-3-mile visibility may give ½-mile identification.
3.	✓	Yes, but would see color of it.	No. (When pressed): Let's say at night I can't.		✓	✓	White or green easier to see than red at night.
4.	✓	✓			✓	✓	Also size of radar blip. Most important is know where you are, where next buoy should be.
5.	✓	✓			Flashing red, flashing white, flashing green.		Know what to expect.
6.	✓		Day—size. Night—how high or how low it is.			Quick flashing vs. regular flashing.	Need binoculars in daylight; not at night.

TABLE A-11. MONITORING RUDDER ANGLE

Situation when monitored	Type of information obtained	Remarks
1. All the time, especially big ship in narrow channel, or approaching another ship.	Loss of steerage due to shallow water. Actions of quartermaster.	Critically important when there's not much time to maneuver.
2. When helmsman is not steering a good course. Every few minutes.		
3. All the time, especially in foggy weather.	Monitor turn direction in fog. Detect slow helmsman in critical turns.	
4. All the time.	Steady course: current, wind, other forces on ship. Generally: check on helmsman.	Very important in dangerous water with strong current—lag between command and effect is too great to depend on swing for noticing incorrect helm action.
5. Always noticing it —particularly in turn.	Bank effects, getting too close, ship is too deep. Check on quartermaster.	Can never trust anybody.
6. All the time in turns. On steady course, if deviation observed.	Turns: check performance of helmsman. Steady course: identify source of difficulty.	

TABLE A-12. RADAR

When used	Purpose	Remarks
1. Poor visibility only.	—	Set just beyond limits of visibility.
2. Poor visibility.	—	—
Dark night.	—	
Something suspicious ahead.	Verify visual navigation.	
3. Visibility below 2 miles.	—	—
Visibility below ½ mile.	Clearly for navigation.	
4. At night all times, especially in good visibility.	Check distance of too-visible buoys.	New regulations are that the radar should be on at all times.
Day, 4-5 mile visibility.	Check oncoming traffic.	
Day, 1 mile visibility.	See how I'm lined up with channel.	
5. All weather.	Anchorage.	
Below buoy-to-buoy visibility.	Navigation.	
6. All weather.	Anchorage.	Individual differences are great. "Some guys might like the radar on all the time...for safety...for their own well-being when the Coast Guard says 'Did you have all your aids for navigation on?'"
Nighttime and so forth.	Check ships, verify visual navigation.	
Visibility 2 or 3 miles and down.	Navigation generally.	

TABLE A-13. NON-VISUAL CUES

Cues mentioned	Remarks
1. Whistle signals, engine noises, gyro repeater, water sound, crew interaction.	
2. Bells and whistles on buoys; lighthouses; engine.	Like to listen to engine—could use tachometer, but can hear things before they show.
3. NO RECORD.	
4. Whistle signals, clicking of gyro.	Signals important in thick fog. New gyros that don't click are a disadvantage.
5. Whistle signals, sounds of buoys, clicking of compass as it turns.	
6. Ship whistles, bells on buoys, foghorns on lighthouses, bells of anchored ships.	Sounds can indicate which way I should turn. In good visibility, they confirm other information.

TABLE A-14. NAVIGATING UNKNOWN CHANNEL

Information or equipment required	Remarks
1. Chart, buoys (or ranges or beacons or lighthouse), magnetic compass.	In order of importance.
2. Magnetic compass, buoys or other visual aids.	
3. NO RECORD.	
4. Buoys, or range with buoy to mark turns; binoculars in daytime; chart (prompted by interviewer) especially because of white-flashing buoys.	Able to navigate Ambrose Channel with ranges and gyro compass, when buoys missing.
5. Gyro compass and chart; buoys; fathometer.	Buoys better than ranges if you know they're on station, because you lose ranges in poor visibility. Compass and chart go together; neither is any good without the other. Buoys not needed if there are known landmarks.
6. Buoys and chart; compass; binoculars.	In order of importance.

TABLE A-15. MONITORING SPEED

Method of determining speed	Situations when needed
1. Tachometer and calibration scale, adjusted for tide, etc., from local knowledge.	Very important approaching anchorage, because of time required to stop ship.
Time how fast you're passing buoys.	Needed for general estimation of arrival time. Important in overtaking another ship.
2. Exact: Time from one point to another.	Not important—you're talking about one or two knots difference.
Ask Captain speeds for different revolutions.	Except important in approaching anchorage.
In close, look at land objects around.	Also important for very sharp turn, and relative speeds are important in overtaking a ship.
3. NO RECORD.	
4. Use table giving speed for given number of revolutions, adjust for current.	Not normally important in New York Harbor.
Exact: Time passage.	In overtaking a ship, relative speed is important—use range-finding capability of radar.
5. RPM is known number of knots. Take time between two buoys.	In most cases, accurate information not needed. Good feeling for it based on experience. Use radar for relative speed when overtaking.
6. Put stopwatch on yourself from one buoy to the next one. Have computer now on ship that tells speed. Ask Captain the speed made at full speed.	Need fairly accurate information for reaching destination at planned time, to avoid causing damage with wash, to know how long it will take to get by a ship being overtaken, to determine starting point for a turn.

TABLE A-16. SELF- AND OTHER-LOCATION

Reporting own location	Reporting other's location
1. Give direction, nearby buoy.	Give buoy or other object.
2. In relation to buoys I'm passing, or distance to known marker.	Marker ship is near.
3. NO RECORD.	
4. Buoy approaching or buoy just passed. Distance from known object.	In the same way as own location, but not as specific.
5. By buoy, beacon, or landmark, in approaching it.	In the same way, unless other is very close to self—as, a tow just ahead of me in or out of channel.
6. Heading and buoy abeam. Distance from known landmark.	In the same way as own location.

TABLE A-17. GENERAL TURNING STRATEGY (Stimulus 9)

- "It's easier for me to say 5° and observe the ship if it's swinging slowly but at the same time starts to come fast. I start with 5°. I don't want the ship going too much the other way. But once you get it going too fast, you can't stop it. So if you get the swing going too fast you may not be able to counteract it with back left. In other words, if I command 20° right rudder, which is answering the same question, 20° right rudder might be too much and it starts the swing like this, and I have to keep the left rudder at 20 , and now that's still going right, so I might have to go hard right and I might not have enough time."

- "I'll give it 20° rudder and then ease it down. Ease the turn down to 10 and to midships and go the other way to stop the swing. I'd have to know the tide and everything, but when you make a turn you make it on the buoy. You'd swing around the buoy. Now it all depends on the size of this channel, 600 foot channels...or width...or 2000 feet. And this all depends, I'd have to show you on a chart. In certain instances you'd come down and the Captain of the ship thinks you're going to hit a buoy and you'd be hanging on that buoy...you'd play it so close that you'd sit in the middle because the ship doesn't turn that fast...so you'd hang right on this buoy knowing that there was water there. I mean some places there is no water for you to get that close to the buoy. (If you can come in close there you do it?) I'd do it. I'd hang on the buoy. If the tide is going. If it's coming this way I would hang on this side and let it set me down into the middle there. (So you're using those currents and things to put you in the right position?) All the time."

- "I want to come around that spot (turn) as quickly as I can, safely... and be on the next course, rather than start with 5° rudder way back in here...and you know your perspective when you're making a slow turn, a real slow turn...your perspective on the buoys doesn't change quickly enough that you can realize where you are."

"In other words you might start drifting sideways and yet it's happening so slowly that all of a sudden you're across the center line of the channel...you don't even know it...now you've got to shift hard over to bring her back and your stern is way over...I would much rather come up to a place where I know I can safely start my turn. I haven't waited too long because I know I've gotten the feel of the ship and come around officially making turns, steady her on the next course and do the same with the next turn."

- "I feel from my experience of all the years I've been piloting... this to me is the most efficient way to do it. Now if I were in a condition of thick fog...which would mean that my speed would be dead slow running up there...I would wait until I got up into this area and then I would put the wheel hard over. I'd put a hard right...and I might even give her full ahead to get her started. But, you know, when you increase the power you increase the speed of the turn. Or if you have your wheel hard over and you don't want to take the rudder off because you want the ship to keep turning, but you want to slow down, you can slow the speed down. You can use a combination of both. In foggy weather I would come up very easy when I was sure I was in a position to make my turn. I'd whip it right aroung—zing—full ahead, hard right, midships, steady up on 322, and rely on the quartermaster to come to a steady course. Now I would move right behind the quartermaster and watch him. And if I saw him when he was at 315 putting the wheel left, I'd say "midships," let her keep coming, and I would guide him like that. The pilot's best friend is the tachometer and the rudder indicator. You always watch those carefully, constantly."

- "--in fact, I challenge myself to use this channel. I've been staying on top of my ship enough to use 10° to see if I can do the whole job. (Oh, and never use more than 10° rudder?) Right, and just as practice on a nice day, just to have, to know it can be done, sometimes you can do it. On some occasions something happens, but if you really think ahead and start early, use a little left before you go to the right, a little right before you go to the left, stay on top of things, you can pull out of it that way."

• "I'll say right 20° rudder as soon as she starts to swing, I'll (pause)--I want to get it going. (You give a big rudder change?) Big rudder change, yes, I want it to come quickly, start quickly but I don't want it to come around quickly...so it's a thing you learn from doing. Everybody has different ideas. Somebody else might start that turn back here, like (name deleted) will turn ships on 5° rudder just to see if he can do it...you know, in safe conditions and so forth. I tried that a few times. I didn't like it at all. I like to get up to that point and make that turn... here's an example...coming down here, this particular turn...when you come up in here you'd normally steer--the course right here is 160--when you pass this point you will steer a 110--near this buoy. Now we have to make a hard left turn and come up to here--well, if you take that turn on 5° rudder from almost the beginning of that turn unitl you're in that position you should be--that buoy's under your bow and is gone. I would rather come over here and then hard left swing it right around and get that buoy on my starboard bow, say "midships" and let it drift up in here, forereaching the position. Now that's me. Another pilot...I never steer 110 over here because I lost that buoy for a couple of seconds. I don't ever like to lose a buoy. That's his way. Now we all bring ships in and out and we don't have that much problem, so actually I can't say that my system is right...but it works, you see it's right for me, but it might not be right for somebody else, because it may make him too nervous to do it that way."

Question 1*: Objective: Improve understanding of physical turning process, and gather general information about turning

Here is a segment of a charted bend. Please draw a line through it to indicate the track you would put a ship through. Mark where you would give commands to change rudder angle (including stopping and starting turn). Mark any other decision points.

Describe how you make this turn as you draw. What do you have to think about? Are current, sheer, etc. more of less important than they are in a straight channel? How do you decide when to start a turn? How do you choose your rudder angle? How do you know when you've put on too much rudder? too little? How soon do you know that the rudder needs changing? How do you know when to stop turning? Will the ship stop turning as soon as you give the appropriate command? Do you pay more attention to where the ship is pointed, or to where it is going? How can you tell where it's going" What do you look at to decide how fast the ship is swinging? to decide who much side slip there is?

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*The numerous questions presented with figures under four numbered items were prompts to aid the researcher in structuring the interview. There was no intent to elicit an answer to each question from each pilot. Rather, the intent was to suggest questions which would cover the desired ideas. There were instances where a pilot could not answer a particular question and other instances when a pilot needed no prompting and easily related the desired information.

NOTE: The figure used by the pilot for the above questions was identical to this figure with the exceptions of the ship, visual angle, line through Point A, Buoys 3 and 4, channel width and distance between buoys which were not drawn on the figure. Pilots were told the dimensions given on this figure and to assume the ship was a 80,000 DWT vessel.

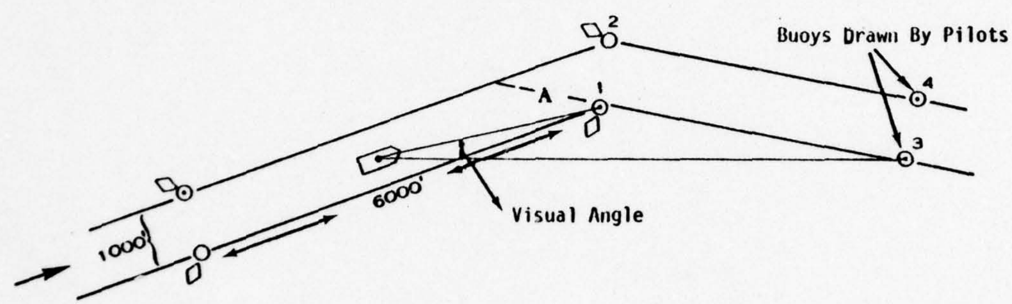

FIGURE A-9. STIMULUS 9—PLAN VIEW OF CHANNEL BEND.

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TABLE A-18. TURNING INFORMATION DERIVED FROM RANGE LIGHTS (Stimulus 10)

(Do you use these range lights to help you make a turn? To decide where to start and/or stop the turn? To determine the rate of turn?)

- "Oh, yes. And I'd be watch ing the bow of the ship--and I would also be watching the range--slippage--on midship. Continue to swing, get almost on range, then turn, steady her up, might have to turn the opposite way."

- (Start turn?) "Yeah, but it's only an aid. You need another factor. The other factor is the buoys. Because unless you can come up on this thing (turn buoys) you don't know how wide this is...how can you come up and change your angle like this unless you know exactly where you are relative to this position? The only other choice you have is coming up like this until this gets exactly on (range lights) and putting the rudder hard over and keep it on."
  (Ending turn?) "Sure. I watch this angle (separation)."

- (Start?) "Yes." (End?) "Yes." (Rate?) "Definitely yes." (Depend on the buoys more than range?) "No. Not depend more on the buoys. But it comes down to the weather conditions; was there a storm before; if there was a storm previous to that day, then I would go by the range. If I knew there was a storm the day before, these buoys could have moved, then I would go by (pause)--I would use both.

- (Start?) "Yes." (End?) "This is the range, going to mark this side of the rock (points to chart of Sandy Hook area). Rather than have to overcompensate by waiting, start early, see what happens. This closing would be very visible and give you good information on how fast you're closing. I'd be watching those ranges more than the buoys. When you have a range, when I see those two lights like that, I'm steady up--that's where I am. I know where the buoy is now 'cause I'm in position. (Does your distance from the range make any difference?) I'm keenly aware of the fact that if I'm further away from the light I can't have the optical spearation that I had when I'm up closer. I don't know what that is but I'm aware of it."

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- "Yes, because it has a fixed position. Sometimes you want to keep it open because it marks a shoal or something."
(Later referred to same rock as previous pilot.)

- (Extended excerpt included because of pilot's examples.)
"Well, I would probably use, rely on those range lights more than the buoys when making the turn if it were something that was most of the time--as a matter of fact when we go into--here, I'll show you (unfolds chart of Sandy Hook area, points to Constable Hook Range). Here's a range, this is all rock, here is one buoy. Now when we come in with a big ship and get up to this area, we start our turn gradually and we aim up in the general direction of this buoy until we can see the range. Now unfortunately, on this particular range they set barrels on it, we don't know why they do it, but when you're on the range, the bright lights almost blind you, but when you're a little bit off you don't see them at all--so they don't help you make the turn. So we have to rely on this buoy to make the turn. We'd rather see that range light cracked way over here (points to area before turn.) They did the same thing over here (points to East River). You can't see it as well as we used to. You can see it a little bit. Now it's the same thing on the East River Range. Particularly when you're coming down the Hudson River and you have to turn into the East River. We used to use the range to judge this turn and now you can't see the range until you're almost on it. So you have to guess when you're getting near that range and it's much more difficult. A range is not only valuable for showing you when you're in the middle of the channel; it's valuable for helping you to make a turn."

(So you would be looking for this (indicating range light stimulus, Figure A-10)?)

" Yes, I would think so--as the range started to close I would be easing up on the wheel. Keeping in mind that this is a given range for a given channel. A channel that I'm familiar with. I wouldn't find a range that valuable if I were a stranger and I would probably rely more on the buoys because I wouldn't know what it would look like or how far it would be cracking. But if it's a place--I know my route by going over and over and over, the range would be very, very valuable."

Note:

The Third District Office of the United State Coast Guard provided information concerning the Constable Hook Range and the East River Deep Water Range. The Civil Engineering Office reported that the Constable Hook Range had been modernized in 1967. Information concerning this range prior to this date was not available; however, it was speculated that the former light probably had a 30° spread. The present light is an FA 240 with an 8° spread. In the near future the spread will be changed to 3.5°. The purpose of the change in 1967 was to increase the visibility of the range. The proposed change is for the same purpose.

The East River Deep Water Range is a Carlisle and Finch 24" fixed light. The candlepower of the front and rear lights is 63,000 and 69,000 respectively. The lights were installed in 1973 replacing an 18" diverging beam light with 150,000 candella for which parts were no longer available. Recently a plate has been added to one of the range lights to decrease the brightness. This was done because local pilots complained the green light was so bright it looked white.

From this information, it is concluded that the interviewed pilot would have been able to see the older range lights a greater distance below the turns than he is now able to do. Thus they are no longer available to "help you make the turn."

Question 2: Objective: determine nature of some of the anticipatory processes in steering.

Suppose you are turning into a channel segment having range lights to mark the center of the channel. As you turn, the lights will look like one or more of these. Which is closest to what it would look like when you give the command to stop turning? Will it continue to look like that? Would you actually use the range to decide when to stop turning? Would you use it to adjust your rate of turning? How?

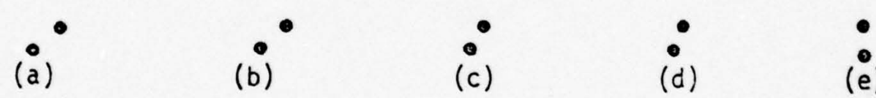

FIGURE A-10. STIMULUS 10—SEQUENCE OF RANGE LIGHT SEPARATIONS.

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TABLE A-19. DESIRED CROSS-TRACK LOCATION APPROACHING TURN

- "Considering no traffic, I would say this is the middle line of the channel. I would be somewhat to the right side of the middle line of the channel."
- "It's a natural tendency to stay on your side of the channel. In actuality, I would probably keep it in the middle. Safer. (Safer, Why?) Because it keeps you from hitting the banks of the channel."
- "If I had a 37 foot ship and this is a 35 foot channel at high tide and I would only have two feet under the ship, I would keep it in the middle. The middle is easy to pilot."
- "We all want the middle, we want the deepest water."

TABLE A-20. WHERE TO START THE TURN

- "Probably when by bow was just about up to that buoy (inside turn buoy) I would estimate. I think that's where I would start. Given that there was no current."
- "I would go at full speed all the way down. This line here--there must be another buoy down there--around the bend. This line between this buoy and this buoy--an imaginary line between these two buoys--comeson to the bow of my ship. I would then start a 10 turn to the right."
- "In the Ambrose Channel they have inbound now for the ships and on the turns we'll ah...there's a buoy here, a buoy here and a buoy there, and when these three buoys are lined up and that's when you start to turn."
- "Let's for example, say that there's a lighthouse up there and land behind it and stacks sticking up like this. You would be able to see that it was starting to move this way or that. I'm starting to get headway that way, because I know I'm going this way. All these factors show me how fast I'm going into the turn. I would look at these buoys. I'd also be aware of how fast they're closing and opening."
- "As you start your turn, you're watching the buoys when they are directly like that. To you, that means you are in a straight line about right here. (Ranging on inside turn buoy and next ahead, same side, buoy)."
- "You take everything in a frame of reference. The most important buoy to make that turn is this one (inside turn buoy), obviously. I'm actually making my turn on this buoy. If everything else is out, I've still got a shot at it by using that buoy. Find that one, find this one, you get a look at everything available... Then when you get up there you start looking ahead at things. (Do you range on the inside turn buoy and the next ahead buoy?) That's how pilots are taught.

TABLE A-21. CROSS-TRACK LOCATION DURING TURN

- "Watching the buoy on my starboard side if I'm making a right turn... if I'm making a left turn, I'm going to watch the buoy on my left side."
- (Side slip in turn?) "I'm watching the buoys and how close I'm getting to them."
- "I turn on the buoy. I'll use the buoy. I'll forget all about this side and work on this turning buoy. Now when I start to see her coming close to that buoy (inside turn buoy), I'll ease the wheel. But I'll always turn on the buoy. I use the buoy as my gauge. I can use this buoy or the buoy that's here. Once I get abeam of that buoy, I'll switch to the next buoy (ahead)."
- "I would want to turn the ship so she would stay in the same relative position, and what I would really want to avoid is getting too close to that buoy when I turn. Because in a dug channel...it has banks on it and when you get a storm—particularly in this channel out of the east—this bank collapses and goes down into the channel... You try and avoid on a turn, getting too close to the buoy because your tendency is to get too close to the buoy. You cut corners if its safe."
- "So what you ideally want to do is get that pivot point up near the buoy as she turns. Okay, now with a ship that has 600 to 700 feet ahead of you, your tendency sometimes is to turn a little early and get yourself too close to the buoy. For the very reason you don't want to overshoot, it's safer to do that than to overshoot. So it's not a problem. You can normally pick that up visually. You find yourself getting too close to it and break the swing a little bit."

TABLE A-22. DETECTING TURNING MOTION

(How do you detect if your ship is turning?)

- --Gyro clicking--

  "Bow of ship, like to stand in center of bridge, go to wings in narrow channel, look at stern when bridge is forward.

- --Gyro, watch and listen--

  (Watch buoys?) "Yes, you can tell how quickly it's cracking as you come around it. Look across bow of most ships... You have to look aft constantly on these ships that have everything forward."

- "Piloting is more of an art than a science, and I think all this comes from doing and having been aboard so many ships that in your own mind a ship fits into a certain notch when you get aboard it... when you've been aboard it for awhile, or you've had the ship before, you can tell when the ship is moving too fast for that--swinging too fast--some of the new rudders have a rate of turn indicator, tells you degrees per second, which I just found out about recently. I wasn't even aware that they had this."

- "The speed, now here is the bow swinging very fast and once I see it starting to swing very fast, I know that the tide's hitting me out here and forcing..."

  (You're watching how fast you swing?) "Right, how fast the bow is going."

  (And you know what looks like "fast" or "too slow"?) "Right. Then I counteract to go the other way."

- "I'm watching the bow of the ship go by that stuff out there. One on one. I'm watching the bow of the ship go by either a buoy or a piece of land, or anything."

Note:

The responses to the questions, "How do you detect if your ship is turning?" and, "How do you know how fast your ship is turning?" are nearly identical. One may conclude that the pilots use the same observables for detecting <u>if</u> the ship is turining and <u>how fast</u> the ship is turning. This is logical and was expected by the interviewers.

TABLE A-23. RATE OF TURN

(How do you know how fast your ship is turning?)

- "You hear a gyro clicking off. Every time it clicks it's one degree and you can hear that--little goodie that nobody knows about--people outside the business. You can't see it (because of the helmsman). You can hear it clicking, though."
- "I watch the bow to see how fast it's moving."
- "The bow of the ship."
- (In fog?) "The clicking noise that it (gyro compass) makes, every degree or half degree. In fact, if I went out on the wing of the bridge to look for this buoy in the fog, I would try to not get too far away so far away so I could hear this clicking to know that--I'm standing right next to the quartermaster--and it starts to go right because I can see it, starting to go right by the compass, it's starting to change degrees and the clicking noise, and now I leave the quartermaster assuming he has the wheel 5° right and he's now clicking on these courses, to 325, 326, 327, 328, and now I walk out on the starboard wing of the bridge to look for this buoy (inside turn buoy, Figure 9-A). I want to make sure I continue to hear this clicking sound. I'm looking at the bow--here's the background, right? I'm looking at the background, there's either a mast or the tip of the bow. Now you'd have a horizon or a background--if it swings this way, maybe that is what I want--that speed across the background.

  (What if the background is just water? Can you still tell?) Yes--the horizon--sure. (Fog?) Fog--no, that's difficult, more difficult. Especially dense fog. You can't tell. (But if you can see your bow, can you tell?) Not in dense fog. (Background is necessary?) Now there's the time you watch your compass very carefully. You watch the gyro compass--and then radar. You are talking about visibility when there is really nothing to see."

  (Let's say you've overguessed how much rudder it's going to take and so you need to correct that. How long does it take before you recognize it's too much?)

  "I would say in a matter of about 30 seconds--less than 30 seconds you would be able to tell."

TABLE A-24. STRATEGY FOR SINUOUS CHANNEL: SHIP'S TRACK (Stimulus 11)

- "You want to stay off the banks. You track the middle and try and keep equal distance from the banks. You stay to the middle or a little right of the middle. Try not to use much rudder. And of course the big kicker is that if you're going slow speed and get in problems, you go full ahead and pull out of it."
- "If I had a ship that was a deep draft in a 1000 foot channel and there was no traffic coming out, I would probably stay towards the center of the channel rather than stay on the right side as the rules of the road would prescribe. As I say when safe and practicable. So the safest thing for an 80,000 ton ship in a 1000 foot channel is probably—particularly is the buoys are equally distant on both sides, not just one set of buoys as we have—I would say the center of the channel or near to the center, the right side of the center. Well, see basically we're looking for safety...that's our big thing... that's what we sell, rather than speed, particularly with bigger ships."
- "To get into basic hydrolics you have to realize you have dug a channel, banks on either side, the water pressure that you are pushing away from you can't be compressed so if you make a turn here and you make it right in the middle of a dug channel, banks on either side, you want to try, unless you have to stay to the right of the channel, you're probably better off with the middle to have equalized pressure on both sides."
- "I would let it get a little to the left side for this particular part of the turn so that when we finished this one we could then steer down this side of this one. In other works, when you come around here from this side, using the suction, using all the factors to help us make this turn, but when we finish this turn we would be on this side of the cahnnel. In other words you would never try to keep it in the middle."
- "Well, first of all, you're violating the rules of the road to start with...the rules of the road state clearly that in narrow channels that your vessel shall keep to that side of the channel which lies on his own right side...and it says when safe and practicable."

Question 3: Objective: Discover if sinuous channel is extension of bends case or different task.

If there were a series of bends such as this, without any significant lengths of straight channel between, what would your procedures be? (Ask subject to draw ship's track.) How far ahead would you anticipate turns? Draw your ship's track for the single bend. This is the way I would do it. Don't you think my track would be easier? Why not? How much work is this sinuous channel compared to a straight channel and compared to a single bend? (Ask subject to use scale of 1 to 10, 10 is very easy and 1 is very difficult.)

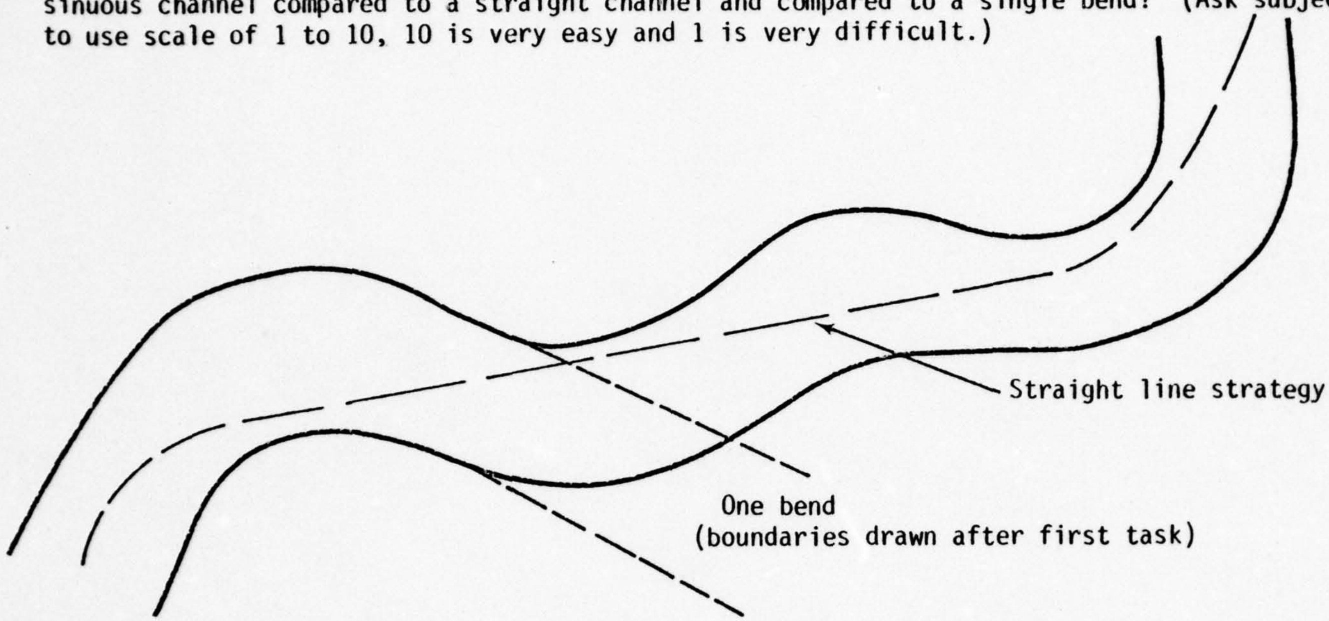

FIGURE A-11. STIMULUS 11—SINUOUS CHANNEL.

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"Basically we would tend, assuming the possibility is always there that there's going to be traffic, we would tend to stay, if this were a real narrow channel with a big ship, we'd want the middle, right in the middle, you'd be talking on the radio and if somebody you were going to meet, you wouldn't want to meet him here—you'd want to meet him on the straightaway, which we do very often."

- "So basically around this area, you'll find most people will stay towards the right side of the center of the channel, if it's a narrow area in a big ship and if it's a wide area in a small ship, you'll stay on the right side of the channel period. There's no reason for just running the buoys down.

TABLE A-25. STATEGY FOR SINUOUS CHANNEL: COMPARISON WITH SINGLE BEND

(Same strategy for one bend as for sinuous channel?)

- "Yes, I would say yes. But I would probably be going slower because of the turns. I think you pretty much think one turn at a time."
- " A sinuous channel. You have to take each turn as a factor. Each one of those turns is a set of factors."
- "You have to think about the second (turn). To make this successful, you have to have made this one the proper way. In other words, if I end up too far over on this side of the channel, that makes this turn a lot more difficult."

TABLE A-26. END-OF-TURN STRATEGY

- "Counteract...till I see the bow stop moving."
- "Well, you don't really actually stop it, because what happens is when the ship started swinging, even if you put the rudder back on midships, it will keep on swinging, so you start easing up on the rudder. If you had 10° rudder and you want to steady it up on the course, we'll put it on 5° , midship, then you could put it the other way to correct it...and steady it up where you want. That's how I usually do it."
- (You counteract them?) "Yes—we call it checking."
- "When I'm here I may be 20°right and even when I'm in the right swing, I'm 20°left counteracting what's going to happen."
- "I would chart where 20° rudder would start to swing pretty fast. You get to this point and then you say 10° rudder, and then you say you're here at midships and midships continues to swing, hopefully by the time you get on this particular spot."

Note:

More information concerning the observables for choosing when to stop the ship's turning motion is needed.

TABLE A-27. INTERVIEWS WITH DELAWARE RIVER PILOTS

The following notes are summaries of responses given by Delaware River pilots during interviews held on January 27, 1978. The interviewers have attempted to factually report the substance of the pilots' comments. No attempt has been made in these notes to state the implications of the responses for the human factors analysis being performed.

Turns

*What do you do differently in making an outside rather than an inside turn?

- Nothing, except when meeting traffic. Then the outside turn buoy may be used for determining when to initiate the turn.

*How do you know when to initiate a turn?

- Estimate the distance to the inside turn buoy, if nothing else is available. (One pilot indicated this strategy even when other aids were visible, but was inarticulate about the method of estimation -- it just "looks right"). Watch the inside turn buoy and the next ahead buoy if both are visible. They form a sort of range. (The inside turn buoy is more important than any other, if you have to do without one.) Watch the range ahead on the new leg -- it's more reliable than the buoys.

  The exact cue used to initiate a turn can't be described, because the turn point changes according to the vessel, how its loaded, wind, current, speed.

*How do you keep track of how the turn is going, to decide whether you need to make adjustments?

- Watch the swing of the bow (one pilot said the stern, because it starts swinging sooner). Swing can be judged by objects ahead, not by objects abeam -- one pilot estimated objects 10^{o} either side of the bow. Also watch the changing aspect of the range and other aids on the new leg. Don't watch the inside turn buoy once the turn is initiated.

One pilot judges swing according to the relative motion of objects (a steeple moving past the trees), not just the motion of objects past the bow. Another pilot explicitly denied such a strategy.

*How do you decide when to give commands to stop the swinging motion and settle on a new course?

- Watch the buoys and the range ahead on the new leg to see how your position is changing. If you're going to wind up on the wrong side, let it swing a little longer so that your new course is back toward your own side. Don't attend to advance in new channel leg.

Distance Estimation

*How do you tell how far away a buoy is?

- Apparent size is a poor cue, because they look bigger from a small vessel than from a large one. One pilot said that the distance is often compared to known distances -- e.g., the widths of one's own ship. Others were inarticulate about the cues used, but one agreed that he probably looks at the extent of water between his vessel and the object in question.

Direction of Motion

*How can you tell if you are not going straight, that you are crabbing?

- Cues used for detection of crabbing are run and observe (explicit), visual angles, ranges of opportunity, changes in ranges and/or visual angles which are not expected such as failure to change or change in the wrong direction. One pilot expressed this idea by stating that the buoys were not changing in the "proper manner".

*Could you tell from watching a single buoy? Does distance to the buoy make any difference in your ability to judge? Better when closer?

- All pilots stated that distance to an object influenced their ability to judge when they were crabbing if only one buoy were available. They agreed that the task was easier when the buoy was closer. They all agreed that using only one object to judge crabbing was possible but difficult. They were not as "confident".

*Do you need to see the buoy against a textured background as opposed to fog or night?

- The pilots stated that lack of background made motion detection more difficult. One added that this was especially true at night.

*Does visibility make a difference?

- Limited visibility made motion detection more difficult because background was removed. One pilot added that the blinking lights at night made motion detection more difficult.

*Can you select a stationary point which is not changing bearing and judge your crabbing rate by that?

- Selecting a stationary point which is not changing bearing to judge crabbing was considered a normal procedure. When available ranges of opportunity are used; an example of range of opportunity would be some part of the ship's structure with a stationary object.

*Can you tell by the wake of your ship? Do you? How often do you look back?

- None of the pilots used the wake or "slick" of their ship to judge direction of motion. They explained that currents disturbed the wake so quickly that it was of no use.

*When you are in a straight channel, what type commands do you give (course or rudder)?

- Pilots indicated that they generally give a course command instead of a rudder command but this was dependent upon how quickly a correction was desired. However, they explained that the correction was primarily a function of distance estimation (how much off the desired course they perceived themselves to be) and the course correction was a conversion from perceived distance off desired track to degrees necessary for the correction.

*Given a ship, compass error, wind and current, how accurately can you estimate a compensated course?

- The range was 1 to 3 degrees. The average estimate was 2^o. Pilots expected more error in their estimates under extreme conditions.

RANGING

*What do you like? (a) Small or large vertical separation (b) Fast or slow closing range? (c) Forward or aft ranges?

- Responses for a and b were judged to be inconclusive because of poorly defined terms. Pilots did not understand the questions, however, they described conditions for a "sensitive" range as being "what they liked". Section c was unanimous. All pilots preferred forward ranges. One explained that an aft range was of no value for turns since it was necessary to be in the next leg and looking back to see an aft range.

*When you are using a range (no buoys of interst, no close banks) and you want to stay off range, what are you observing to maintain the desired position? (a) Are you trying to maintain a constant split? (b) Are you maintaining a constant distance from edge or center?

- Pilots state that they maintain a constant split and a constant distance from the edge. When they described the process it was apparent that they have a learned, dynamic memory of the range split for a number of cross track locations. They are conscious that the split changes for a given cross track location as they sail toward the range.

NIGHT NAVIGATION

*What do you do differently at night when piloting? Do you look for patterns? Buoy to buoy?

- Pilots expressed no variations in perception method for night navigation. Most agreed that it was more difficult at night but they used the same pattern and mental lines used during the day. The color of the lights and their blinking patterns were used for identification at night.

RADIO AIDS

*What radio aids do you use? Does the percent vary with weather conditions or time of day?

- All reported using RADAR where accuracy of distance estimation was critical such as anchorage, meeting and passing. One young pilot prefers to have it on all the time to allow checks on his distance estimations. It is used extensively in poor visibility, however, all the pilots preferred visual nagivation to RADAR navigation. In general, RADAR was used more at night than daytime.

  The pilots stated that LORAN-C and other "electronic equipment" was not practical for river navigation because it takes too much time and attention away from visual navigation.

MENTAL LINES VS. VISUAL ANGLES

*How do you navigate a channel in an open area marked with a single line of buoys?

- Pilots reported using lighthouse sectors and a run and observe technique.

*Do you imagine a line through the buoys marking the channel edge?

- Yes, imagine parallel lines of ship's direction of motion and line of buoys. One pilot did not report imaginary lines.

*Do you watch the split or degree to which the buoys are closed?

- Yes, very much. All agreed.

*Do you watch one buoy and then switch to another buoy — buoy-to-buoy navigation?

- Only a young pilot described using buoy-to-buoy navigation.

*When you imagine a line connecting buoys on the edge of the channel, do you trace it back with your eyes and judge its distance abeam?

- No. All pilots judge position in the channel by looking ahead. The young pilot reported that he had never looked abeam, even when learning, although conscious of a line, he learned to maintain his distance by what the aids ahead of him looked like.

MEMORANDUM

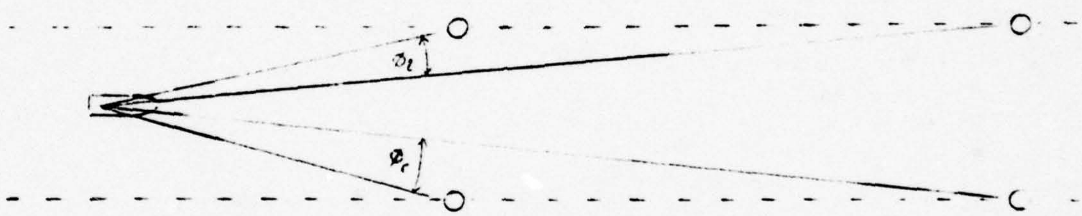
17 January 1978

TO: Distribution

FROM: Duane Small

SUBJECT: Visual Angle Matching

Consider a ship positioned near the center of a channel marked with gated buoys:



We have regarded the ratio ϕ_ℓ/ϕ_r as the observable for judging cross-track location in this situation, and our model requires quantitative information on the error associated with judging such ratios. Based on consultation with psychophysics expert John Baird, I propose that σ_R, the standard deviation of judgments of a ratio R, be computed from:

$$\sigma_R = (.5|\log R|+.1)R \tag{1}$$

The formula is based on experiments in which subjects are asked to judge the size of one angle (the <u>comparison</u>) with reference to a known angle (the <u>standard</u>). Alternatively, subjects may be asked to produce a comparison of a given size, using the standard as a reference. Either way, it will be useful to distinguish among:

- t_c, the average judged (or produced) comparison size
- σ_{t_c}, the standard deviation of judgments (or productions) of the comparison
- T_c, the true (or instructed) size of the comparison
- T_s, the true size of the standard.

Qualitative Considerations

Weber's Law predicts that, when $T_c = T_s$, $\sigma_{t_c}/T_s = K$. Dr. Baird's analysis of experimental data suggests that it is more profitable to express the relationship as $\sigma_{t_c}/t_c = K$; note that $T_c = T_s$ and that, in this situation, experiments show that $t_c \doteq T_c$. The conversion permits extension of Weber's Law to other situations, including those in which the comparison is regularly underestimated or overestimated. In general, for any one ratio T_c/T_s, $\sigma_{t_c}/t_c = K$, but K is an approximately linear function of the absolute value of the logarithm of T_c/T_s. Furthermore, $t_c = T_c^n$ for any fixed standard. For estimating lengths with standard and comparison at the same distance, n varies from slightly below to slightly above 1. We should be well served by assuming $t_c \doteq T_c$ regardless of the ratio T_c/T_s.

Based on the foregoing, it is possible to obtain:

$$\sigma_{t_c}/t_c = a|\log T_c/T_s| + b. \tag{2}$$

Since the units of measurement are arbitrary, we can let $T_s = 1$; then $t_c \doteq T_c = R$, the ratio of the angles, yielding:

$$\sigma_R/R = a|\log R| + b. \tag{3}$$

Quantitative Estimates

When $T_c = T_s$, σ_{t_c} is from 3 to 10 percent of t_c, depending on experimental conditions. The mariner's view of the channel corresponds to rather poor experimental conditions, particularly since the angles to be judged are not

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adjacent. Dr. Baird therefore suggested we use the 10 percent figure. Letting $\sigma_R/R = .1$ when $R = 1$, we obtain a value of .1 for b in Formula 3.

The ratio of σ_{t_c} to t_c reaches 60 percent when T_c and T_s are in a ratio of 10 or 20 to 1, either way. Consistent with Dr. Baird's suggestion of using the larger estimates of error obtained in experiments, I have assumed 60 percent at the 10 to 1 ratio. Letting $\sigma_R/R = .6$ when $R = 10$ (or .1), and using $b = .1$, we obtain a value of .5 for a in Formula 3. Formula 1 then follows directly.

Dr. Baird repeatedly referred to Figure 3.10, p. 66, of his Psychophysical Analysis of Visual Space in discussing angle comparison. I have reproduced that figure below and have superimposed on it a line representing the proposed error function. It can be seen that the formula provides for higher error, but yields the same general relationship between error and ratios, as in the experiments represented.

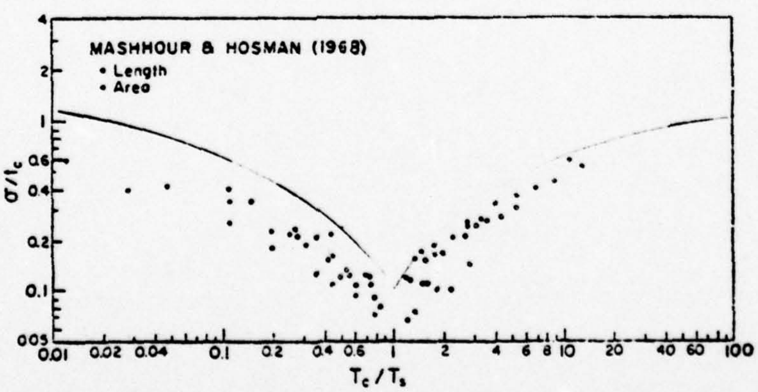

FIG. 3·10. Relative error, standard deviation divided by the mean (σ/t_c), as a function of theoretical ratios (T_c/T_s) for area and length. The coordinates are logarithmic. For more details, see the text.

MEMORANDUM

22 March 1978

TO: Distribution

FROM: Duane Small

SUBJECT: Informal Experiment Using Channel Perspective Simulator

Purpose: Gather preliminary quantitative data comparing gated and staggered buoy patterns. Gather preliminary quantitative data comparing daytime and nighttime pattern use.

Method: One observer estimated cross track location as presented on the channel perspective simulator. Repeated estimates were obtained under three conditions. In the first condition, the near three pairs of buoys were lighted (continuously on) to provide the pattern that would be provided by gated buoys in daytime. In the second condition, the left buoys of the first and third pair and the right buoys of the second and fourth pair were lighted (continuously on) to provide the pattern that would be provided by staggered buoys in daytime. In the third condition, the buoys of the first three pairs were lighted intermittently to provide a pattern typical of gated buoys at night. The light characteristics of all buoys were .5 seconds on in a 4-second cycle; phase was randomly assigned.

In each condition, the simulator was set at 10-foot intervals from the right edge to the center of the simulated 1000-foot channel. The center and the right edge were each shown ten times, and every other position was shown twice. The order of presentations was random, and the observer was not informed of either the proportion of times each stimulus was shown nor the exact range of stimuli. The observer was aware that the simulator could not display locations very far to left of center.

For center and right edge positions, the standard deviation of errors of estimating location was computed directly. For locations 50, 150, 250, 350, and 450 feet from the edge, the variance of estimates was approximated by two methods, and the standard deviation was taken as the square root of the average of the two approximations. Both approximations were based on 22 observations, 2 from each of the 11 locations within 50 feet of the point for which the standard deviation was being computed. One approximation was analogous to the usual variance computation: An average squared deviation was computed. But instead of using the deviation from the mean, the deviation was taken from the actual location being estimated, as adjusted by any difference between the average estimate and the average of the locations being estimated. The second approximation was obtained by using the correlation between estimated and actual locations to determine the proportion of variance not accounted for by correlation; that proportion was then multiplied by the variance of the actual locations used in the computation.

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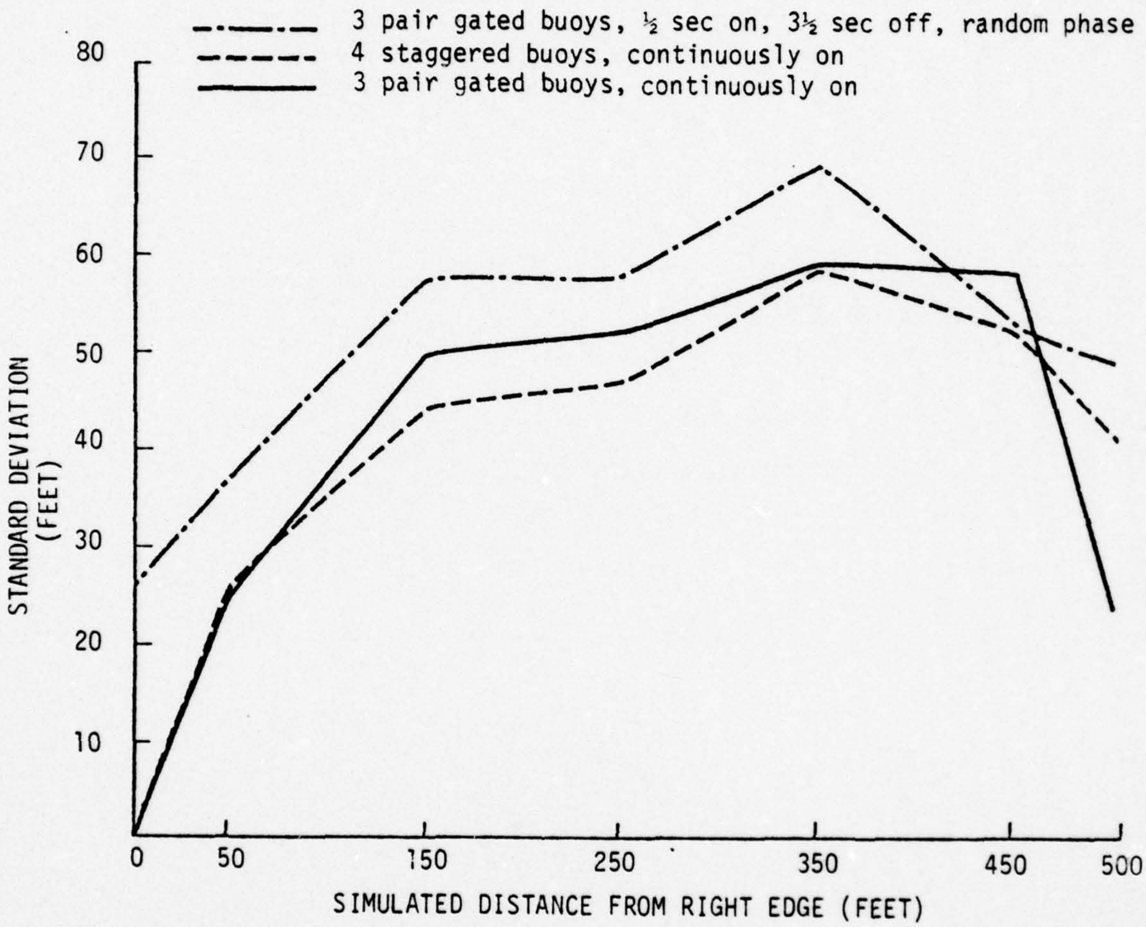
Results: The estimated standard deviations of error for the three conditions are plotted below.



Distribution:
E. Lofgren
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F. Varcolik

CHANNEL PERSPECTIVE SIMULATOR

The channel perspective simulator is a large board, painted a flat black, containing four red and four green lamps. The lamps are arranged to be in the identical perspective as four pairs of buoys in a 1000' wide channel when viewed from the correct point (100" from the front edge of the simulator and 2" above that edge). The first pair of buoys simulate a distance of 3000' and each succeeding pair an additional 6000'. The luminous intensities of the lamps are scaled to the inverse square of the scaled distance.

A linkage permits moving the lamps so that the observer sees them as they would appear from any selected distance from the channel edge.

The lamps are controlled by a timing circuit with a nominal four-second cycle consisting of sixteen quarter-second segments. Any lamp may be turned on or off at the beginning of any segment, and the settings for any lamp are independent of the settings for the others. Options exist for leaving lamps continuously on or continuously off. Since the lamps are all driven by the same timing circuit, the phasing of their on-off cycles remains constant.

EXPERIMENTAL REPORT

SENSITIVITY TO CHANGES IN OFF RANGE POSITION

Harbor pilots have indicated in interviews that they customarily use ranges, not only to establish and hold a position on range, but also to maintain a position off range by a constant amount. Furthermore, their references to keeping the buoys along the edge of a channel "split" or "open" suggest that they treat edge-of-channel buoys in the same way, using them as a range and maintaining a position a constant distance from the channel edge, which would be the on-range position.

Several studies have shown an influence of vertical separation of ranged objects on the ability to maintain an on-range position (see Arnold and Woodward, 1977, for a review). It may be expected that horizontal separation, which is induced by moving off range, will similarly have an effect on the ability to maintain a fixed position off range. It is the purpose of this study to examine variability in judging how far a range is open (i.e., the size of the horizontal separation) as a function of both horizontal and vertical separation.

Horizontal and vertical separation of the ranged objects are defined in terms of visual angles, not in terms of physical coordinates. Thus, when two objects are on range, there is no horizontal separation, even though the objects may be several miles apart. The visual angle separating them is entirely vertical; if the higher object were lowered sufficiently, the two objects would be super-imposed in the visual field, and no separation between them would be seen. By the same token, a vertical separation between objects may occur even if they are in the same plane. When two buoys in the plane of the water are viewed from the height of a ship, an expanse of water will be seen between them even if one is directly behind the other.

It is to be hoped that the present experiment will be applicable to maintaining a position off the edge of a channel, as well as to maintaining a position off range with respect to formally defined range marks. The fact that pilots talk about the split of the buoys suggests that an experiment on ranging is appropriate to the task of staying away from a line of buoys. And since height of eye produces vertical separation, as noted above, both variables in the present study should be relevant.

The possible equivalence of staying off the edge of a channel and staying off range suggests a hypothesis that needs to be evaluated in the experiment. Analysis of the edge-of-channel situation shows that, for a given height of eye, the slope of an imaginary line connecting two buoys is affected only by distance from the channel edge, not by distance to the first buoy or by distance between buoys. In contrast, both vertical and horizontal separation of the buoys are affected by distance to the first buoy and distance between buoys, as well as by distance from the channel edge. Thus slope, which is the ratio of vertical to horizontal separation, may well be the observable used in staying away from the channel edge. It is also possible that slope is the relevant variable for ordinary ranges. The correct slope for holding a particular distance off range would be different for different distances from the range, but the correct horizontal separation also changes with distance.

The experiment was designed to permit evaluation of judgment variability as a function of slope, as well as to allow evaluation of it as a function of horizontal and vertical separation. Values of horizontal and vertical separation were chosen in such a manner that the combinations formed a small number of sets, with the slope the same within each set.

Method

Observers

Three paid volunteers served as observers. Prior to being accepted for the experiment, they were tested to make sure they had normal near-vision acuity. Corrective lenses were permitted.

Task

Stimuli were designed to simulate what a mariner sees when viewing open range objects such as two buoys or a set of range lights. Observers' sensitivity to changes in the openness (horizontal separation) of such range objects was tested by presenting them with a series of trials, each consisting of a standard stimulus followed by a comparison which might or might not differ from the standard. For each trial, the observers' task was to judge whether the comparison was identical to or different from the standard.

Apparatus

All stimuli were automatically presented on the screen of a Plasmascope® intelligent computer terminal, which was operated as a stand alone device. Observers responded to stimuli by pressing designated keys on a keyboard associated with the terminal. All responses were automatically recorded on floppy discs by the terminal's internal computer.

An adjustable chin rest was located on a table one meter from the computer screen to ensure that the visual angle subtended by each stimulus remained constant throughout the experimental sessions.

Stimuli

The standard stimuli consisted of two .84 x .84 mm filled red squares. The vertical distance between the two squares was either 6.72, 13.44, 26.88, or 53.76 mm. The horizontal distance was also one of those four values. All possible combinations of distance relationships between the stimuli were used to produce 16 different

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"Plasmascope" is a registered trademark of Science Applications, Inc.

standard stimuli. The distance between squares was measured from the center of each square. One square was always located below and to the left of the second square.

Associated with each standard stimulus were two comparison stimuli. One comparison was identical to the standard. The other comparison had the same vertical separation as the standard, but its horizontal separation was slightly larger than that of the standard (i.e. the lower square was farther to the left of the upper square). The size of the difference between a standard and its unlike comparison was not the same for all standards. On the basis of preliminary testing, a value was chosen which produced an error rate of about 25% in a series of trials in which half the comparisons were the same as the standard and half were different. The objective was to choose a difference which would not be perfectly detected, yet would be detected at better than a chance level. Either perfect responding or chance level responding would make it impossible to measure sensitivity to differences using signal detection analysis. (The 25% error level chosen, assuming errors were equally distributed between incorrectly saying "same" and incorrectly saying "different", would correspond to a value of 1.35 for the sensitivity measure d'.)

The horizontal separation, vertical separation, and horizontal deviation (difference between standard and unlike comparison) are presented in Table 1.

Each time the standard and comparison were presented on the computer screen, they appeared in randomly selected locations, although the designated distance relationship between squares was maintained. This was accomplished by random assignment of the midpoint of an imaginary line connecting the two squares to a position in a 8.4 x 8.4 mm square at the center of the screen. Thus, judgments could not be based on relationships between stimuli and particular screen locations.

Design

The selection of the standard stimuli establishes a complete fastorial design with horizontal and vertical separation as the independent variables. The particular values chosen also permit analysis in terms of a derivative independent variable. Slope is defined as the ratio of the vertical to the horizontal separation. The sixteen stimuli represent seven values of slope: A slope of 1 is represented by four stimuli; slopes of 1/2 and 2 are each represented by three stimuli; slopes of 1/4 and 4 are each represented by two; and slopes of 1/8 and 8 are each represented by one stimulus.

The 16 standard stimuli define 16 experimental conditions. Each condition consisted of 40 trials, with the standard and one of its comparisons presented in each trial. In one half the trials the comparison was identical to the standard and in the other half, the comparison was different from the standard. The like and unlike comparisons were presented in random order. Each observer received each of the 16 experimental conditions in a different random order on each of eight days.

A measure of sensitivity expressed in terms of standard deviation units was derived for each condition on separate days and for each condition collapsed over days for each subject. The first 10 trials of each condition were ignored as an allowance for warm-up effects. Of the remaining trials, those on which the standard and comparison differed were treated separately from those on which the standard and the comparison were the same. The proportion of hits was taken as the proportion of correct responses for trials on which the stimuli differed; the proportion of false alarms was taken as the proportion of incorrect responses for trials on which the stimuli were the same.

The proportions of hits and false alarms were referred to a table of the normal distribution, and associated standard scores were obtained. Subtracting the standard score for false alarms

TABLE 1

DISTANCES ASSOCIATED WITH EACH STANDARD

	Standard		Unlike Comparison
	Vertical Separation in mm	Horizontal Separation in mm	Horizontal Deviation in mm
1.	6.72	6.72	.84
2.	6.72	13.44	1.26
3.	6.72	26.88	2.10
4.	6.72	53.76	2.94
5.	13.44	6.72	.84
6.	13.44	13.44	1.68
7.	13.44	26.88	2.52
8.	13.44	53.76	3.78
9.	26.88	6.72	1.68
10.	26.88	13.44	2.10
11.	26.88	26.88	2.94
12.	26.88	53.76	4.62
13.	53.76	6.72	1.68
14.	53.76	13.44	2.52
15.	53.76	26.88	2.52
16.	53.76	53.76	4.62

from the standard score for hits yielded an estimate of d', a dimensionless measure of sensitivity from signal detection theory. The size of the difference between the horizontal separation of the standard and the horizontal separation of its unlike comparison (horizontal deviation) was divided by d', producing an estimate of the standard deviation of errors in judging the size of the horizontal separation of the standard stimulus.

Procedure

Observers were read a set of instructions providing a detailed explanation of the nature and objective of their task. A brief discussion of the mariner's task of using range objects in order to regulate his ship's position in a channel was presented to provide the observers with an understanding of the stimulus materials used in the experiment. Observers were informed that, in each condition, the comparison would differ from the standard on exactly half the trials. They were told that it was just as important to notice that the comparison was different from the standard when, in fact, it was different as it was to notice that the comparison was the same as the standard when, in fact, it was the same. They were asked to make as few errors of either kind as possible and to try to respond consistently.

The observer initiated each of the trials within an experimental condition by pressing a designated key on the terminal keyboard. After a one second delay, the standard appeared for two seconds. Two more seconds intervened before the appearance of the comparison, which also remained on the screen for two seconds. Immediately following the comparison, a request for a response appeared on the screen, after which the observer could initiate the next trial.

The three observers were run individually in nine sessions, each lasting about 2.5 hours. The first session was devoted to instructions and to giving the observers practice on their task. The remaining sessions were the eight experimental sessions. In

each session the sixteen experimental conditions were preceded by a warm-up condition. One minute rest periods were provided between conditions, with five minute rest periods after the sixth and eleventh experimental conditions. The experimenter was present during all sessions.

Results

The estimated standard deviations computed from the daily sessions were analyzed by means of the Friedman F statistic to check for effects of horizontal separation, vertical separation, and observers. The data from each observer were also analyzed to detect any tendency for performance to change from day to day.

Standard deviations increased with increasing horizontal separation and with increasing vertical separation. Both effects were significant. For horizontal separation, $F(3) = 223.34$, $p < .001$; for vertical separation, $F(3) = 37.13$, $p < .001$. Observers differed significantly in their performance, $F(2) = 66.37$, $p < .001$, and one of the three observers showed significant variation from day to day, $F(7) = 14.86$, $p < .05$.

Many of the scores which entered with the foregoing analyses had to be approximated because, on a given day's session, an observer had made either no false alarms or no misses, resulting in an indeterminately large sensitivity. When that occurred, a score was computed by assuming that the probability of a false alarm or of a miss was .01 for the 30 trials in question. There was also, in one session, for one observer, one condition in which performance was below chance, resulting in an indefinitely small sensitivity and a standard deviation of infinity. While such scores do not cause serious problems for rank-order tests like the Friedman, they are not suitable to parametric analysis. Consequently, the parametric analyses described below were performed on

collapsed data. Sensitivities and standard deviations were computed by taking into account the 240 trials for each condition accrued by each observer over all eight sessions. When proportions of hits and of false alarms were computed for the combined data, no proportions of 1 or 0 were obtained. Therefore, all sensitivity scores and all standard deviation estimates were finite. The collapsed data are presented in Table 2.

The appropriateness of slope as a means of describing the open range observable was tested through two regression analyses. For these analyses, the dependent variable was taken to be the standard deviation of changes in slope, which was obtained by multiplying the original standard deviation (or horizontal separation) by the slope and dividing by the sum of the horizontal separation and the original standard deviation.

The first analysis tested whether horizontal and vertical deviation contributed to the dependent variable in any way other than what could be expressed by their ratio, which is slope. Regression analysis was performed in two stages. In the first stage, the dependent variable was predicted from two variables representing observers and from a sixth-degree polynomial in slope, which takes out all degrees of freedom associated with slope. At that stage of the analysis, the multiple correlation coefficient R is .98706, and the residual sum of squares is .06045. In the second stage, third-degree polynomials in horizontal and vertical separation were added to the equation, taking out all additional main effects for those two variables. At the second stage, $R = .98726$, and the residual sum of squares is .05950. The difference in the residual sums of squares is the sum of squares associated with the improvement in prediction caused by adding the main effects of horizontal and vertical separation. Dividing that difference by the degrees of freedom associated with those effects, and dividing the result by the residual mean square after the second step, yields a significance test for improvement in prediction, $F(6,32) = .085$, $p > .99$.

TABLE 2

STANDARD DEVIATIONS OF ERROR IN OBSERVING THE HORIZONTAL SEPARATION OF SIMULATED RANGE OBJECTS, ACCUMULATED ACROSS EIGHT SESSIONS

	Condition		Standard Deviation (mm)		
	Vertical Separation (mm)	Horizontal Separation (mm)	Observer 1	Observer 2	Observer 3
1.	6.72	6.72	.52	.33	.42
2.	6.72	13.44	.82	.69	1.04
3.	6.72	26.88	1.53	1.30	3.04
4.	6.72	53.76	2.47	2.50	3.54
5.	13.44	6.72	.68	.47	.77
6.	13.44	13.44	.84	.59	.95
7.	13.44	26.88	1.65	1.44	1.98
8.	13.44	53.76	3.51	1.76	3.64
9.	26.88	6.72	.67	.53	.71
10.	26.88	13.44	1.07	.67	1.28
11.	26.88	26.88	1.85	1.06	2.94
12.	26.88	53.76	2.31	2.27	5.44
13.	53.76	6.72	.99	.64	.90
14.	53.76	13.44	1.15	1.09	1.55
15.	53.76	26.88	2.47	1.57	2.57
16.	53.76	53.76	3.55	1.92	5.13

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The second regression analysis was performed because of the inherent confounding of slope with horizontal and vertical separation. In the second analysis, the dependent variable was predicted by variables representing observer effects, by third-degree polynomials in horizontal and vertical separation, and by crossproducts of those polynomials. The result is a prediction equation which includes all possible degrees of freedom associated with the independent variables, regardless of how they are described. For this analysis, $R = .98751$, and the residual sum of squares is .05832. The fit of this complete model may be compared to the fit provided by a slope description by testing it against the first stage of the previous regression analysis. The difference in the residual sum of squares is .00213, and the difference in the degrees of freedom is 9. Obtaining a mean square and dividing by the residual mean square of the second model provides a test of the improvement in fit of the second (complete) model over the fit provided by the slope-only model. For this test, $F(9,29) = .18$, $p > .99$.

In order to obtain a best-fit curve for predicting standard deviation of changes in slope as a function of slope, a stepwise regression analysis was performed using a sixth-degree polynomial of slope as the prediction. Since on-range position represents an infinite slope, we deemed it best to obtain this fit for a redefined slope. Slope was recomputed as horizontal separation divided by vertical separation, and the dependent variable was similarly redefined as the original standard deviation (of horizontal separation) divided by the vertical separation.

The stepwise analysis proceeded first by forcing out the variance associated with observer effects. For observers, $R = .22643$; based on the residual after the last significant improvement in the model, $F(2,44) = 11.09$, $p < .001$. Although this variable contributed significantly to the prediction equation, observer effects accounted for only 5 percent of the variance.

After observer effects had been forced into the equation, stepwise regression proceeded normally. The first variable selected was slope, making $R = .94781$. The effect of slope is significant, $F(1,44) = 366.643$, $p < .01$. The next variable selected was the fifth power of slope, which did not significantly improve the prediction, $F(1,43) = 3.830$, $p > .05$. The least squares prediction equation based on significant variables is

$$\sigma_S = .01518 + .05390\ S \quad ,$$

where S is slope (as redefined) and σ_S is the standard deviation associated with observations of slope. This equation, along with the variables reflecting observer differences, accounts for 90 percent of the variance in the data.

Although no significant improvement on slope could be found for predicting variability expressed as changes in slope, we thought it advisable to determine a best fit equation based on horizontal and vertical separation, when variability is expressed as changes in horizontal separation. Therefore, we performed another stepwise regression analysis, this time with the original standard deviations (of horizontal separation) as the dependent variable and with third-degree polynomials of horizontal and vertical separation, along with their crossproducts, as predictors.

Once again variance due to observer differences was forced out first. With the dependent variable expressed as changes in horizontal separation, observers produce $R = .36765$; based on residual of the best-fit model, $F(2,43) = 17.382$, $p < .01$. The significant differences among individuals is confirmed, although only 13 percent of the variance is accounted for. With observer effects forced into the equation, the first variable selected was horizontal separation, $R = .89986$. Based on the best-fit model, the improvement is significant, $F(1,43) = 173.409$, $p < .01$. The second variable selected was vertical separation, $R = .91254$, $F(1,43) = 5.909$, $p < .05$. The third variable selected was the

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third power of horizontal separation, which did not produce a significant improvement, $F(1,42) = 1.499$, $p > .05$.

The best-fit equation for predicting variability of horizontal separation is

$$\sigma_H = .06150 + .01003\ V + .05431\ H \quad ,$$

where σ_H is the standard deviation associated with observations in horizontal separation, H is horizontal separation, and V is vertical separation. All terms are expressed in millimeters; the constant must be changed for any change in the basis of measurement. This equation accounts for 83 percent of the variance in the observations.

Discussion

The results indicate that the observable associated with the openness of ranged objects can appropriately be characterized as slope. No other description of the stimuli used in the experiment could improve on slope in predicting the data from the experiment, when variability in observation was expressed as changes in slope. Furthermore, variability in observing changes in slope was a simple linear function of slope, whereas variability in observing changes in horizontal separation was a function of vertical as well as of horizontal separation.

The large percentage of variance accounted for by the prediction equation for slope is supportive of the interpretation offered above. However, differences in the percentage accounted for by the slope equation and by the horizontal and vertical separation equation should be interpreted with caution. Estimates of standard deviation, however expressed, tend not to be normally distributed, and the exact distributions will be affected by the

transformations involved in expressing them as standard deviations of slope or standard deviations of horizontal separation. The differences in distributions could be responsible for some of the apparent difference in the quality of the prediction equations.

The variability estimates obtained represent viewing under close to optimal conditions. Observers were seated in a quiet room, free from distractions, with nothing to attend to but their perceptual task. Furthermore, the delay between standard and comparison was as short as was consistent with avoiding a sensation of movement due to the random positioning of the stimuli. Delays between observing a range from a particular position and observing it from a slightly different position are surely variable and are likely to be larger than those employed in this experiment. Consequently, error in using a range is likely to be larger by some modest factor than that measured in this experiment. However, the functional relationship between openness and variability should be unchanged.

There is some reason to be cautious in extending our prediction equation all the way to a slope of zero. On general principles, it is risky to extrapolate a prediction curve past the range of the data on which it is based. But beyond that, there is some indication that information is processed differently when a range is nearly closed. While selecting stimuli for the experiment, we noted that when horizontal and vertical deviations were very small, the size of the simulated range objects became important. We found ourselves doing such things as comparing the right edge of the lower square to the left edge of the upper square. Consequently, our prediction equation may apply only to the point that such effects begin to be relevant.

Some consideration should be given to the fact that there were statistically significant differences among observers, and that for one observer there were significant day-to-day variations.

The day-to-day variation indicates the importance of designing future experiments in a manner similar to this one, with all conditions experienced on each day. Otherwise, differences that were really caused by daily fluctuation could be attributed to differences in conditions. The differences among observers are potentially more troublesome, since they raise questions concerning the generalizability of our results to other observers -- specifically to experienced mariners. Fortunately, the differences among observers were small compared to the differences associated with how far the range was open. The prediction equation based on slope, ignoring observer differences, accounts for 85 percent of the variance in the results, compared with 5 percent due to observer differences. Consequently, we expect the results to generalize quite well. However, the experiment should be repeated using a pilot or two as observers just to make sure that the results are not substantially different.

Reference

Arnold, B. Y. and Woodward, K. G., Residual Error in Using a Range to Obtain a Line of Position. Washington: Ocean Engineering Division, Office of Engineering, United States Coast Guard Headquarters, January 1977.

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Arnold, B.Y. & Woodward, K.G., Residual Error in Using a Range to Obtain a Line of Position. Washington: Ocean Engineering Division, Office of Engineering, United States Coast Guard Headquarters, January 1977.

Summarizes studies of ability to hold an on-range position. Error varies with the vertical separation of the range lights or marks, and with the type of mark. Computational suggestions are made for estimating error in using ranges of opportunity.

Brown, B., Effect of Background Constraint on Visual Search Times. Ergonomics, 1976, 19, 441-449.

Studied effects of backgrounds differing in regularity (statistical constraints) on the time required to find a target. Up to a point, time increased with increasing homogeneity of the background; then it more or less levelled off, but declined slightly for one highly practiced subject.

Location of target relative to type of background area (filled or unfilled) was not examined. Author's review suggests lack of good research on that aspect.

Clarke, A.A., Human Factors Aspects of Ship Handling. Feltham, Middlesex, England; The Ergonomics Laboratory, EMI Electronics Ltd., 1977.

General discussion of human factors, with few specifics. Does include a reference to study of training of distance estimation.

Offers an information-processing assessment of electronic navigational aids.

Fell, J.C., A Motor Vehicle Accident Causal System: The Human Element. Human Factors, 1976, 18, 85-94.

Gives taxonomy of human factors involved in auto accidents. Considers accident-causing and accident-severity-increasing factors regarded as "human effects" (perception failure, comprehension failure, decision failure, action failure) and accident-relevant conditions ("human causes" of the above "human effects" -- physiological failure, driver condition, driver experience, driver preoccupation, risk-taking behavior).

Galanter, E. & Galanter, P., Range Estimates of Distant Visual Stimuli. Perception & Psychophysics, 1973, 14, 301-306.

Reports several experiments of magnitude estimation of distance, mostly over water, using large distances.

Power functions were fitted, with exponents from .8 to 1.27. They argue that distance is therefore not likely to be a direct input to operations in space, unless transformed in the manner of a TOTE system.

Error is not reported, but plots of data points suggest approximately the same error for difference distances when plotted on log paper. (error proportional to distance).

Hagen, M.A. & Elliott, H.B., An Investigation of the Relationship Between Viewing Condition and Preference for True and Modified Linear Perspective with Adults. Journal of Experimental Psychology: Human Perception and Performance, 1976, 2, 479-490.

Compares naturalness of various drawings of figures in isolation. True perspective is generally not the most natural. The authors suggest that we always imagine pictures as being at a viewing distance of about ten times the size of the objects depicted, regardless of the viewing distance of the picture.

Harvey, L.O., Jr., & Michon, J.A., Detectability of Relative Motion as a Function of Exposure Duration, Angular Separation, and Background. Journal of Experimental Psychology, 1974, 103, 317-325.

Found larger thresholds for detecting relative motion at larger initial angles of separation. Thresholds were lower for longer exposures -- close to the same for 2 and 4 seconds, the longest exposures used. At 4 sec., 7.5' initial separation gave .3'/sec threshold, 2^{o} gave 3.5'/sec.

Rate of separation was not constant, and one light was stationary.

Huffner, J.R., Pilotage in Confined Waterways of the United States: A Preliminary Study of Pilot Decision Making (CG-U-96-76). Linthicum Heights, Md.: Maritime Institute of Technology and Graduate Studies, July 1976. (NTIS No. AD A029715).

Contains protocols of pilot interviews and of running commentary during trips through pilot waters. Protocols are related to ongoing events during trips, and videotapes are available. Data are largely unstructured and unanalyzed.

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One commentary is pilot's self-report of thought processes, with little questioning or prompting.

Johnston, A.W., Cole, B.L., Jacobs, R.J., and Gibson, A.J., Visisbility of Traffic Control Devises: Catering for the Real Observer. Ergonomics, 1976, 19, 591-609.

Central theme: design of visual systems for real-world use should not assume "normal" vision in the user population.

Provides some data on task-performance deterioration with decreased acuity and color deficiency. Several tasks; oriented toward highway systems.

Kinchla, R.A., Visual Movement Perception: A Comparison of Absolute and Relative Movement Discrimination. Perception & Psychophysics, 1971, 9, 165-171.

Presents mathematized theory of absolute and relative motion perception, relating the former to the latter through memory.

Relative judgments occur only at separations less than 15°. (Experiment showed 8-10° separation made relative and absolute judgments the same.)

Suggest extension to length judgments under successive presentation.

Mankin, D.A., The Influence of Perceptual Anchors and Visual Noise on the Vertical-Horizontal Illusion. Perception & Psychophysics, 1969, 5, 149-154.

Placed dots on horizontal line to get effect of anchor on measuring off length equal to vertical line via a cursor. Could not replicate illusion even in no-anchor, no-noise (random dots in field) condition.

Value for our purpose is reference to studies on anchoring effects in scaling.

Miskie, D., Dainoff, M., Sherman, R., & Johnson, L., Does Distance Perception Change as the Degree of Enclosure Changes; Some Psycho-physical Studies Under Real and Simulated Conditions. Man-Environment Systems, 1975, 5, 317-320.

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As spaces become more open, far distances tend to be increasingly underestimated. The authors express this as a power function relating true and judged distance, with a lower exponent for open than for enclosed space. Data are reported only for the real conditions, not for the simulated ones.

Mourant, R.R. and Langolf, G.D., Luminance Specifications for Automobile Instrument Panels. Human Factors, 1976, 18, 71-84.

Chief contribution for our purposes is notes on effect of loss of brightness and contrast senstivity in older people.

Applies above to letter-reading task at short distance.

Reference list includes sources of more basic information.

Navon, D., Forest Before Trees: The Precedence of Global Features in Visual Perception. Cognitive Psychology, 1977, 9, 353-383.

Four experiments supporting claim that a larger, wholistic pattern is processed prior to an analysis of the components from which the pattern is made.

Within limits, shows part-whole relationship rather than size to be controlling factor.

Owens, D.A. & Leibowitz, H.W., Oculomotor Adjustments in Darkness and the Specific Distance Tendency. Perception & Psychophysics, 1976, 20, 2-9.

Suggests that distance perception changes as a function of reduced cues, since a dark-adapted accommodation and a dark-adapted convergence exist (there are individual differences, and the two do not correspond). Perceived distance is related to the convergence adaptation.

Literature cited suggest applicability to Ganzfeld as well as to dark point. Application to night (and day) navigational aids would have to be determined.

Pollack, M. and Williams, K.E., An Experimental Investigation of Collision Avoidance Aiding and Human Performance using CAORF. Presented at the Conference on Human Factors in the Design and Operation of Ships, Gothenburg, February 1977.

Compared collision-avoidance performance using vision only, radar only, or automated CAS (graphically displays area into which one should not proceed), measured in terms of distance between ships at point of closest approach, etc. CAORF simulation study.

Smith, S.L., Angular Estimation. Journal of Applied Psychology, 1962, 46, 240-246.

Studied the ability to either set a knob or switch, or to verbally estimate, the heading of a radar trail. Accuracy was not affected by the length of the trail (5/16 to 1 1/2 in. simulated trails; 1/8 to 1 in. pen drawings of trails). Mean error was about 7 degrees for airmen, about 4 1/2 degrees for civilians for knob setting, higher for verbal estimation.

Warren, R., The Perception of Egomotion. Journal of Experimental Psychology: Human Perception and Performance, 1976, 2, 448-456.

Tested ability to identify direction of simulated motion over an endless plain. Speed was 1.25 units per second, with a unit being equal to the simulated altitude. With various directions of motion, the mean constant error was 5.56 degrees to the right, with a standard deviation in pointing error of 5.18 degrees. Static linear perspective and mechanical pointing controls are also reported.

Wist, E.R., Diener, H.C., & Dichgans, J., Motion Constancy Dependent Upon Perceived Distance and the Spatial Frequency of the Stimulus Pattern. Perception & Psychophysics, 1976, 19, 485-491.

Perceived speed increases linearly with perceived distance when angular speed is held constant. The slope of the linear function increases linearly with spatial frequency. Lowest spatial frequency was 0.022 cycles/deg (spatial period 45 deg). Highest was 0.088 cycle/deg (period 11.25 deg). Visual field only 22 deg -- apparatus described in referenced article.

Worley, J.K. & Markley, R.P., Distance Discrimination in a Reduced Cue Setting. Psychonomic Science, 1969, 17, 237-238.

Obtained difference limen for sequential presentation of moon module (then unfamiliar) with reduced cues to simulate outer space.

For increasing distance, $DL=.0062D^{1.29}$

For decreasing distance, $DL=.0088D^{1.26}$

The average for the two was $DL=.0076D^{1.27}$

D is in feet. Tests were at 400, 900, 2100, and 3200 ft.

BASIC ANALYTIC TECHNIQUE FOR
DESIGN & EVALUATION OF SYSTEMS OF
AIDS TO NAVIGATION

APPENDIX B
MATHEMATICAL MODELING AND METHODOLOGY

JULY 1978

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APPENDIX B

MATHEMATICAL MODELING AND METHODOLOGY

I. HUMAN FACTORS MODELING

1.0 Introduction

This section of Appendix B presents the human factors modeling that was accomplished during Phase I of the Aids to Navigation Requirements program. The majority of the material in this section was previously transmitted to the U.S. Coast Guard in the form of monthly progress reports or briefings. This section essentially contains excerpts from those transmittals. Since the Appendix is designed to provide back-up material to the main report, no attempt was made to establish a smooth flow-through of the material. This section should be read only as more detailed discussions of material presented in the main technical report.

2.0 Modeling of Observables

Our human factors investigations indicate that a limited set of characteristics of the A/N system define reference points for the estimation of navigation variables (position and motion of the vessel). These characteristics, or observables, are the aspects of the A/N which are observed and used for navigation. The mathematical modeling of the human factors information has the objective of developing probability contours to specify the ship position and motion that would be expected if navigation depended on a specified A/N system. The approach is to model the relationships between the observables and the navigation variables. For any given A/N system there are errors associated with the observables, since they permit only imperfect estimation of the navigation variables by the mariner. Using the mathematical relationships between the observables and navigation variables, the errors in the observables are propagated (or mapped) to the navigation variables. The errors in the navigation variables are then used to develop the probability contours. This section summarizes the Phase I human factors modeling for the straight channel scenario.

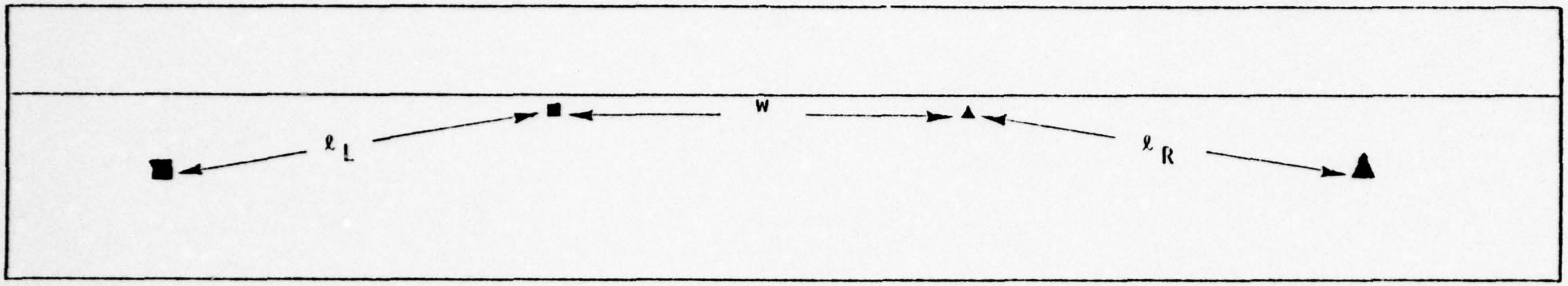
2.1 Example Error Propagation

The navigation variables for the straight channel scenario are cross-track position and ship's direction of motion. Only cross-track position is considered here, since direction of motion is generally set by the run and observe navigation process. For the case of gated buoys, there are three reference points for cross-track position: the two edges of the channel, where the buoys lining the edge are in range; and the center of the channel, where the visual angles subtended by the lines of buoys are equal. Figure B-1 illustrates these reference points. Mariners position themselves in the center of the channel by matching these visual angles, while mariners near the channel edge range on the near-edge line of buoys. Thus two cases for the straight channel scenario are defined: (1) navigating down the center of the channel, and

CENTER-OF-CHANNEL REFERENCE POINTS

EQUALITY OF VISUAL ANGLES SUBTENDED BY ℓ_L AND ℓ_R

w = APPARENT CHANNEL WIDTH AT DISTANCE OF LAST VISIBLE BUOY PAIR



EDGE-OF-CHANNEL REFERENCE POINT

RANGING ON BUOYS MARKING NEAR CHANNEL EDGE

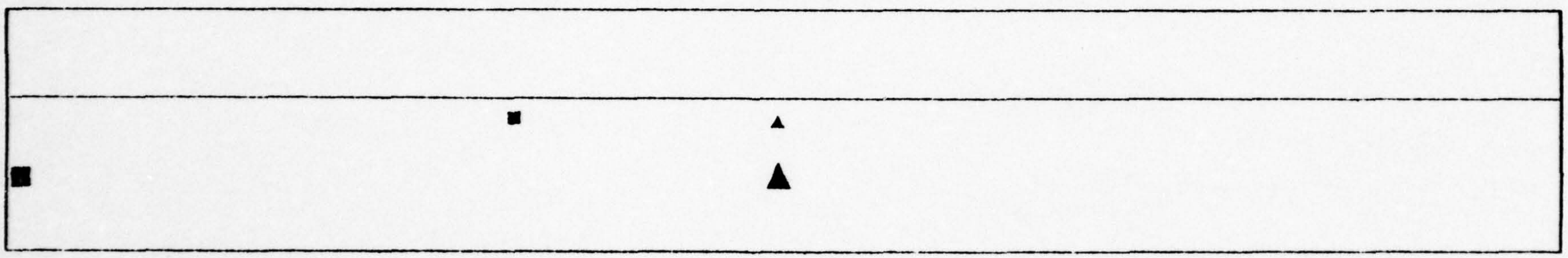


FIGURE B-1. REFERENCE POINTS FOR STRAIGHT CHANNEL

(2) navigating near one edge. Navigating in other portions of the channel are undoubtedly combinations of these two primary cases.

For the straight channel, center-of-channel case, error equations were developed that relate the observables to the navigation variables. These error equations are discussed in the next section. The models are based on the perspective view as seen by the mariner and contain the height of eye of the observer. Matching of the visual angles by the mariner was modeled as the ratio of the visual angles. This ratio was treated as the observable, and, through consideration of perspective geometry, related to cross-track position, P. (Error equations were also developed for the straight channel, edge-of-channel case, and are discussed in the following sections.)

Example standard deviations in cross-track position were developed for the center-of-channel region to determine the relative sensitivity to several characteristics of the A/N. The number of visible buoy pairs (N) and the distance of the ship to the first buoy pair (d) were varied, and the effects on the standard derivations were noted.

The example standard deviations were obtained by propagating hypothesized errors in the center-of-channel observable (ratio of the visual angles $\emptyset_R \emptyset_L$. The gated buoy, center-of-channel error equation presented in the next section was used for this error propagation. The error propagation technique used is based on generalized least squares, and was illustrated in Appendix B of our proposal. This is a standard statistical technique and will not be discussed further here.

Errors in the mariner's ability to compare and equate the visual angles formed by the lines of buoys on either side of the channel were hypothesized from the results of a simplified inhouse experiment. Members of the SAI A/N team were used as subjects. Obviously the standard deviations reported herein are valid only for the purpose of ascertaining the sensitivity to the characteristics of the A/N that were varied

(N and d). (This analysis was conducted early in the program with preliminary error estimates and is presented only to illustrate sensitivities. We have since obtained much better data concerning the ability to match errors, but the analysis shown here was not redone because of time constraints. The σ_p maps shown in a later section were generated from the correct data, and should not be compared to the results herein.)

Table B-1 lists the standard deviations of the navigation variables resulting from the error propagation. Twelve cases were run corresponding to two, three, and four visible buoy pairs, ship distances of 2000 feet and 4000 feet from the first buoy pair and desired cross-track positions of channel axis and 100 feet to the right of the channel axis. As can be seen, the number of buoy pairs (as long as at least two pairs are visible) and the distance to the first buoy pair do not affect the mariner's ability to fix his cross-track position if he is near the center of the channel.

Table B-1. STANDARD DEVIATIONS FOR CROSS-TRACK POSITION

Desired Course is Center of Channel
P = 500 ft.; I = 6000 ft.; height of eye = 60 ft.; channel width = 1000 ft.

N	d (ft)	σ_p (ft)
2	2000	50
2	4000	50
3	2000	50
3	4000	50
4	2000	50
4	4000	50

Desired Course is 100 ft. to Right of Center of Channel
P = 4000 ft.; I = 6000 ft.; height of eye = 60 ft.; channel width = 1000 ft.

N	d (ft)	σ_p (ft)
2	2000	61.0549
2	4000	61.0576
3	2000	61.0548
3	4000	61.0569
4	4000	61.0543
4	2000	61.0567

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2.2 Example Error Models

Error models relating the A/N observables to the navigation variables were developed for each of the cases analyzed during Phase I. Example error models are presented in this section.

Center of Channel, Gated Buoys

Near the center of the channel, our human factors investigation has indicated that the mariner uses the equality of the visual angles subtended by the buoys lining each side of the channel to position himself with respect to the channel center. Thus, the observable is the relative magnitudes of these visual angles. We have modeled this process of comparison as the ratio of the visual angles, $\emptyset_R/\emptyset_L$. Figure B-2 illustrates the visual angles $\emptyset_R$ and $\emptyset_L$, ignoring the dip due to the height of observer. However, we have included the dip angle in the mathematical model.

In the mathematical equations, the right-hand channel edge is taken as the point of origin for defining cross-track position, P. The error equation for cross-track position is developed from perspective geometry by relating the ratio of the subtended angles (observable) to the navigation variable (P). This error equation is:

$$\emptyset_R/\emptyset_L = \sqrt{\frac{D^2(W-P)^2 + [d(D+d)DIP]^2}{D^2P^2 + [d(D+d)DIP]^2}} + \varepsilon_R \qquad (1)$$

where:

$$\text{DIP (radians)} = \frac{KhD}{d(D+d)} - \frac{d}{c}$$

$K = 9.9636 \times 10^{-4}$

$C = 4.8128 \times 10^{4}$

h = height of eye in feet

d and D are defined in Figure B-2 in feet $\times 10^{-3}$

P = cross-track position in units of channel width, W

ε_R = hypothesized error reflecting mariner's ability to match $\emptyset_R$ and $\emptyset_L$.

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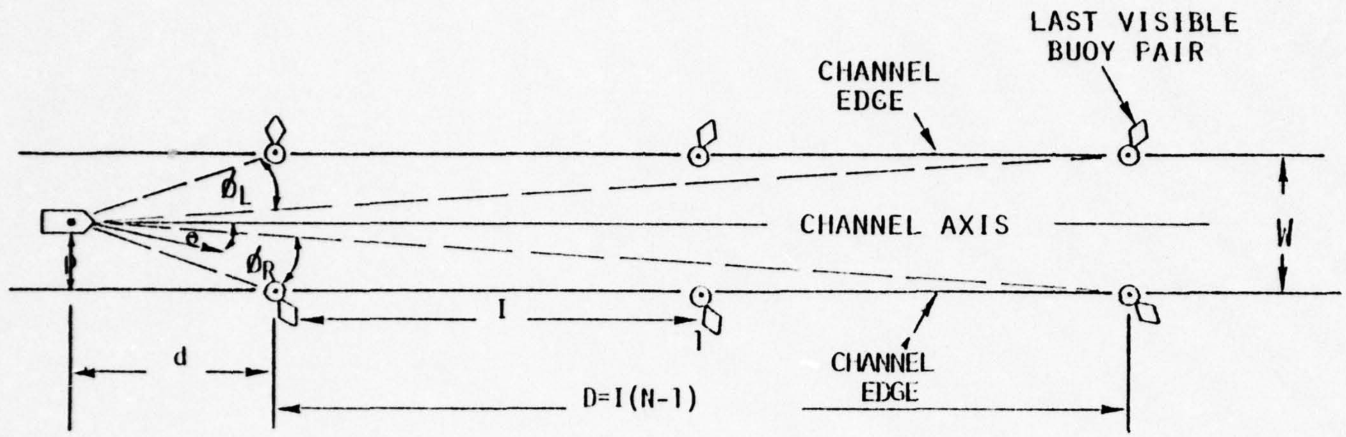

IN THE ABOVE FIGURE, THE NUMBER OF BUOY PAIRS (N) IS 3.

FIGURE B-2. GEOMETRICAL ARRANGEMENT OF SHIP AND A/N STRAIGHT CHANNEL, GATED BUOYS

This error equation was used to develop the example standard deviations presented in the previous section, and the errors for gated buoys in the σ_p map, presented in a later section.

Errors were propagated from the observable (ϕ_R/ϕ_L) to cross-track position (P) using a standard error propagation technique based on generalized least squares and the law of covariance propagation. In broad outline, the approach is as follows:

- Linearize the error equation by expanding in a Taylor's series and truncating after the first order term.
- Couch the linearized error equation in matrix notation as an expedient to manipulation and understanding.
- Express the ship cross-track position as a linear function of the observable utilizing the matrix formulation of the least squares estimator.
- Utilize the matrix formulation of the law of covariance propagation to estimate the covariance matrix containing the variance of the ship cross-track position that results from using the observable for control. This covariance matrix completely specifies a normal distribution for ship position reflecting the ability of the mariner to estimate cross-track position from the observable.

The error equation is linearized by expanding in a Taylor's series about an arbitrary estimate of cross-track position and truncating after the first order term. In the operational case, where the objective would be to estimate the ship cross-track position, the "arbitrary point" would be an initial estimate or "guesstimate" of this parameter. For the case at hand, this arbitrary point is academic since it will not appear in the final error propagation expression; it is considered here only for the development of these expressions.

The truncated Taylor series expansion is:

$$\phi_R/\phi_L - \phi_R'/\phi_L' = \frac{\partial\ (\phi_R/\phi_L)}{\partial P} \Big/ \, p' \ \Delta P + \varepsilon$$

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where:

$\emptyset_R/\emptyset_L - \emptyset_R'/\emptyset_L'$ = difference between the "true" observable, $\emptyset_R/\emptyset_L$ and the observable $\emptyset_R'/\emptyset_L'$ that would result from the specification of the arbitrary estimate p'.

$\frac{\partial (\emptyset_R/\emptyset_L)}{\partial P}$ = the partial derivative of the error equation with respect to the ship cross-track position, P, evaluated at the arbitrary cross-track position p'.

$\Delta P = P - p'$ = the difference between the "true" cross-track position P, and the arbitrarily specified cross-track position p'.

ε = error term.

The above equation is the linearized error equation, exhibiting the desired property that the observation is a linear function of the ship cross-track position. Standard least squares techniques now apply.

The set of linearized condition equations can be expressed in matrix terminology as follows:

$$\overline{y} = \overline{x} \cdot \overline{\beta} + \overline{\varepsilon}$$

$$\emptyset_R/\emptyset_L - \emptyset_R'/\emptyset_L' = \frac{\partial (\emptyset_R/\emptyset_L)}{\partial P} \cdot \Delta P + \varepsilon$$

The least squares estimator for $\overline{\beta}$ is:

$$\hat{\overline{\beta}} = (\overline{X}^T \overline{W} \overline{X})^{-1} (\overline{X}^T \overline{W} \overline{Y})$$

where

$\hat{\overline{\beta}}$ = estimator for $\overline{\beta}$

$\overline{X}^T$ = transpose of $\overline{X}$

$\overline{W}$ = a weight matrix which is the inverse of Σ_y, the covariance matrix of the observations. Σ_y has the form:

$$\Sigma_y = \sigma_{\emptyset_R/\emptyset_L}$$

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The above weighted least squares estimator is referred to in the literature as the "BLUE" estimator (Best Linear Unbiased Estimator) and provides the necessary linear relationship to propagate errors in the observable to the ship cross-track position.

The law of covariance propagation is a standard statistical technique for propagating errors from the domain of a linear relationship to the range of the relationship. It is shown in the literature that if a set of stochastic variables, $\overline{D}$ (the range) is linearly related to another set of stochastic variables, $\overline{E}$ (the domain) e.g.,

$$\overline{D} = \overline{A}\ \overline{E}$$

where $\overline{A}$ is the matrix of linear coefficients that define the linear relationship, then the covariance matrix of $\overline{D}$, $(\Sigma_{\overline{D}})$ is:

$$\Sigma_{\overline{D}} = \overline{A}\ \Sigma_{\overline{E}}\ \overline{A}^T$$

where $\Sigma_{\overline{E}}$ is the covariance matrix of $\overline{E}$. In the least squares estimator for $\overline{\beta}$ set:

$$\overline{A} = (\overline{X}^T\ \overline{W}\ \overline{X})^{-1}\ \overline{X}^T\ \overline{W}.$$

Then

$$\hat{\overline{\beta}} = \overline{A}\ \overline{Y}$$

and the covariance matrix for cross-track position is:

$$\begin{aligned}\Sigma_{\hat{\overline{\beta}}} &= \overline{A}\ \Sigma_y \overline{A}^T \\ &= (\overline{X}^T\ \overline{W}\ \overline{X})^{-1}\ \overline{X}^T\ \overline{W}\ \Sigma_y \overline{W}^T\ \overline{X}\ (\overline{X}^T\ \overline{W}\ \overline{X})^{-1} \\ &= (\overline{X}^T\ \overline{W}\ \overline{X})^{-1}\end{aligned}$$

since $W = \Sigma_y^{-1}$, and $\overline{W}^T = \overline{W}$. The above equation is the expression used to propagate errors in the observable to the ship cross-track position.

Estimating Cross-Track Position from Apparent Slope of Buoy Line

The postulated observable for the edge of channel case is the apparent slope of the channel edge made visible by buoys marking the edge. The view seen by an observer transiting a straight channel is shown in Figure B- 3 . The element of information postulated as the observable is the apparent slope of the line on the water which corresponds to the channel edge. Any buoys or beacons on that line will indicate a slope determined solely by height of eye (h) and distance from the channel edge (P). The slope is not influenced by the along-track distance to the buoys or their spacing. The slope is the ratio of the horizontal visual angle (caused by the distance to the channel edge) to the vertical visual angle (caused by dip). Rigorously it is:

$$\text{SLOPE} = \frac{840 \tan^{-1} P}{1+47.4718h} \quad \text{(From experiment)} \qquad (2)$$

where P is the distance from the channel edge in feet x 10^{-3} and h is the height of eye in feet.

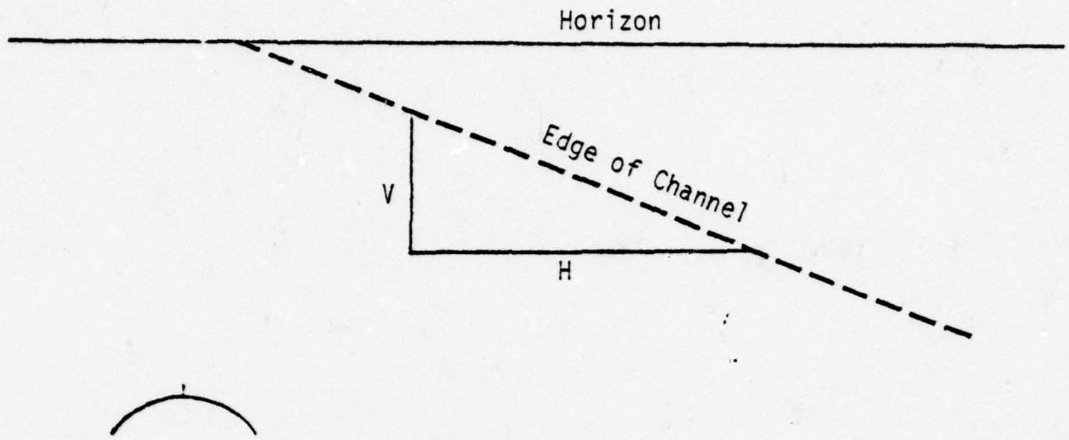
Equation (2) can be very closely approximated by:

$$\text{SLOPE} = \frac{P}{h} \qquad (3)$$

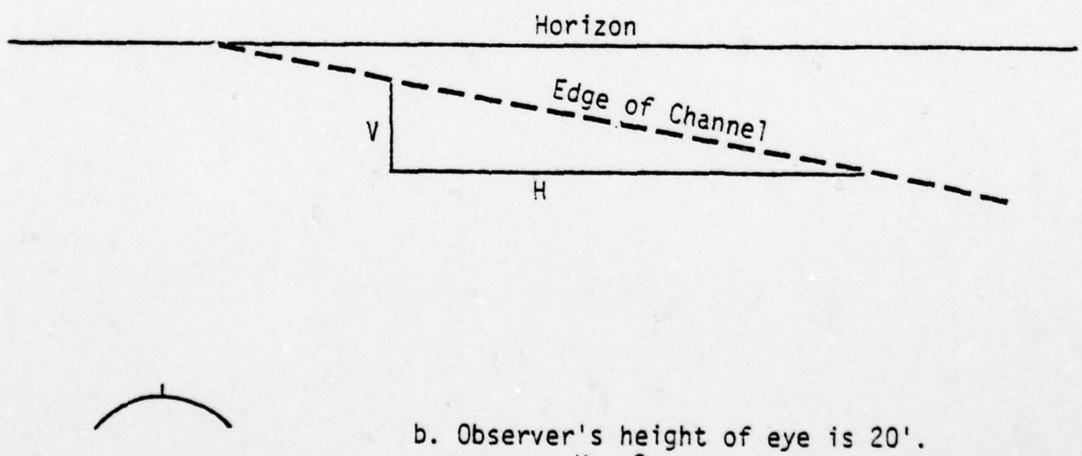
where P and h are in the same units.

Figure B-4 shows a graph of m vs. P and h with both the rigorous and approximate values plotted.

The simplicity of the relationship may be a clue to the actual psychological process involved in estimating cross-track position from buoys marking a channel edge. The slope vs. P is highly linear in the regions of interest.



a. Observer's height of eye is 60'.
Slope = $\frac{V}{H} \approx \frac{P}{h} \approx 2.5$



b. Observer's height of eye is 20'.
Slope = $\frac{H}{V} \approx \frac{P}{h} \approx 5.$

FIGURE B-3. VIEW SEEN BY AN OBSERVER 150' FROM CHANNEL EDGE

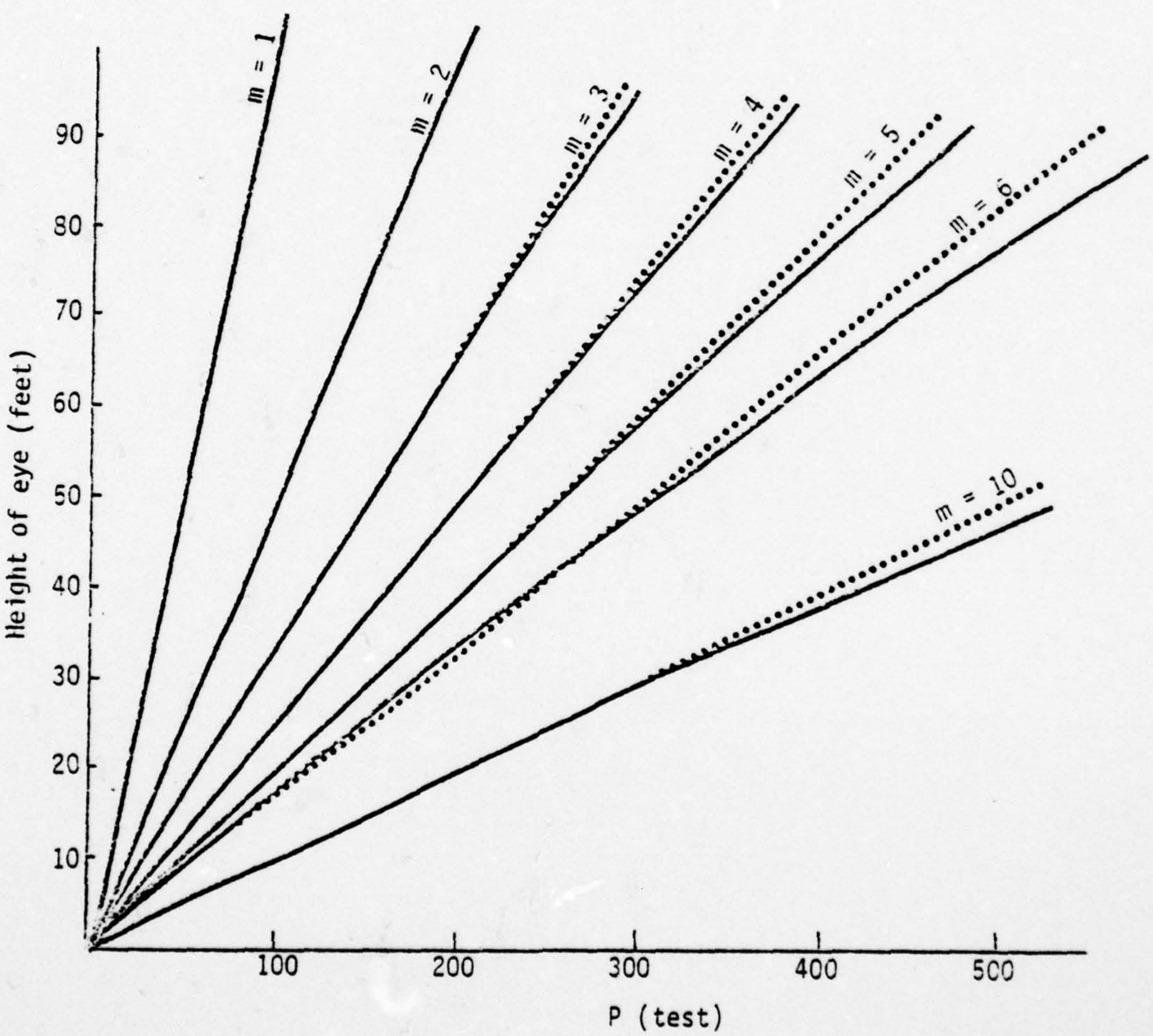


FIGURE B-4. APPARENT SLOPE OF OBJECTS ON CHANNEL EDGE

A reference point for this observable is when the slope is zero, i.e., at the channel edge. Using this reference point, it should be possible to obtain a preliminary, very general idea of the nature of the error in estimating P for various heights of eye. In general, the error in estimating cross-track position should increase as the slope increases, since the psychological task involved should be easiest at the edge of the channel, where the slope is zero. Also, self analysis using the perspective diagrams has indicated to us that the task of judging P from slope appears to be more difficult for lower heights of eye, indicating, perhaps, that P can be fixed more accurately for smaller slopes. For the purposes of this analysis, we will postulate that the ability to fix P using slope is better for large heights of eye. The slope increases as the distance from the channel edge increases for a given height of eye, and increases as the height of eye decreases for a given distance from the channel edge. The character of the error in slope necessary to satisfy both these arguments will be examined, namely that the ability to fix P increases as P approaches the reference point, and increases with increasing height of eye.

Suppose one postulates that the error using the observable slope to estimate P were constant over all values of the slope, i.e.:

$$\sigma_m = K.$$

Then the error in P resulting from using slope as the observable to estimate P is obtained from the approximation expression, Equation (3) as follows:

$$P = mh.$$

Using the law of covariance propagation to propagate the assumed error in m to P,

$$\sigma_P^2 = \left(\frac{\partial P}{\partial m}\right)^2 \sigma_m^2$$

so that

$$\sigma_P = hK. \tag{4}$$

(286)

This assumption for the error in slope would result in an error in fixing P using slope that is constant for all cross-track positions. This violates our assertion (for which there is some experimental evidence) that the error in fixing P should increase as one moves from the reference point (the channel edge). Also, Equation (4) indicates that the error in fixing cross-track position increases with the increasing height of eye. But we are asserting that increasing height of eye should decrease the error in fixing cross-track position. For these reasons, we tentatively reject the postulate that the error in fixing cross-track position by observing slope is constant for all slopes.

Suppose we now postulate that the error in using slope to estimate P is a linear function of slope, i.e.,

$$\sigma_m = Km.$$

Again using the law of covariance propagation, the error in P for a given height of eye is:

$$\sigma_P = hKm.$$

Or, substituting Equation (2) for m in the above:

$$\sigma_P = KP. \tag{5}$$

This assumption for the error in slope implies that the error in estimating P does not depend on height of eye. This again violates our assertion that decreasing height of eye should increase the error in fixing P.

It appears from the foregoing that the error in slope must increase with slope at a rate greater than linear if all of the following assumptions are to be satisfied:

- Slope is the observable used to fix cross-track position.
- The error in fixing P increases with P for a given height of eye.

- The error in fixing P increases with decreasing height of eye for a given P.

As a first-order guess, in order to generate preliminary probability distributions, the error in estimating slope is assumed to be proportional to the square of the slope, i.e.:

$$\sigma_m = Km^2.$$

Then the error in fixing cross-track position, P, using slope as the observable, is:

$$\sigma_P = \frac{KP^2}{h}.$$

Thus, the error in fixing P would increase as P^2 for a given height of eye, and would increase linearly as height of eye decreased for a given P. To first-order, this relationship has characteristics that satisfy both assertions concerning how the error should behave in excursions about P and h.

Testable hypotheses from the foregoing analysis are the following:

- Estimating P using slope would be relatively insensitive to the distance to the first buoy.
- This process should be relatively insensitive to buoy spacing, or the number of visible buoys as long as at least two are visible (assuming the buoy survey error is negligible). This hypothesis is based on experimental data which indicate that the ability to determine angle is insensitive to the length of line defining the angle.
- The ability to fix cross-track position should deteriorate at a rate faster than linear as cross-track position is moved from the channel edge.

Resolution of these hypotheses would tend to substantiate both the fact and the nature of the observable, and the nature of the observable error.

(The edge of channel cases assessed in Phase I used the above quadratic relationship between the observable slope and the navigation variable cross-track position. An experiment was conducted (Appendix A), the results of which indicate that a linear relationship between slope and cross-track position is an excellent approximation. However, the results of this experiment were obtained too late in the program to influence the edge of channel assessments.)

Range Error Model

Figure B-5 illustrates the range geometry. The observable for the range is the horizontal component of the visual angle subtended by the front and rear ranges, Ø. When the observer is off the range axis by some distance P, this visual angle is a function of the ratio of the observer's distance from the front beacon (D) to the distance between the range beacons (R). Error in relating the observable Ø to the distance off-range, P, arises from two sources for the case where the mariner is familiar with the range, namely, errors in his knowledge of distance to the range (D), and errors in the observable (Ø). Thus, there are two components of error that must be treated in the range case, that due to the distance estimation to the range, and that due to errors inherent in relating a visual angle at a given range to a distance off-range. Only the case where the mariner is familiar with the range was treated in the Phase I program.

The error equation for ranges is:

$$\emptyset = \tan^{-1}\left[\frac{PR}{(PR)^2+(DR)^2+DR}\right]+\varepsilon \; . \qquad (6)$$

This equation forms the basis for the error propagation to obtain standard deviations of P. Propagation of error in Ø and D to P requires a double mapping procedure. First, the error in D is propagated to the domain of the error equation. The result after this propagation is that there are effectively two components of error in Ø; the original error in the observable, $\sigma_{\emptyset}$; and the propagated error

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$$\phi = \mathrm{TAN}^{-1} \frac{PR}{PR^2 + D(D+R)}$$

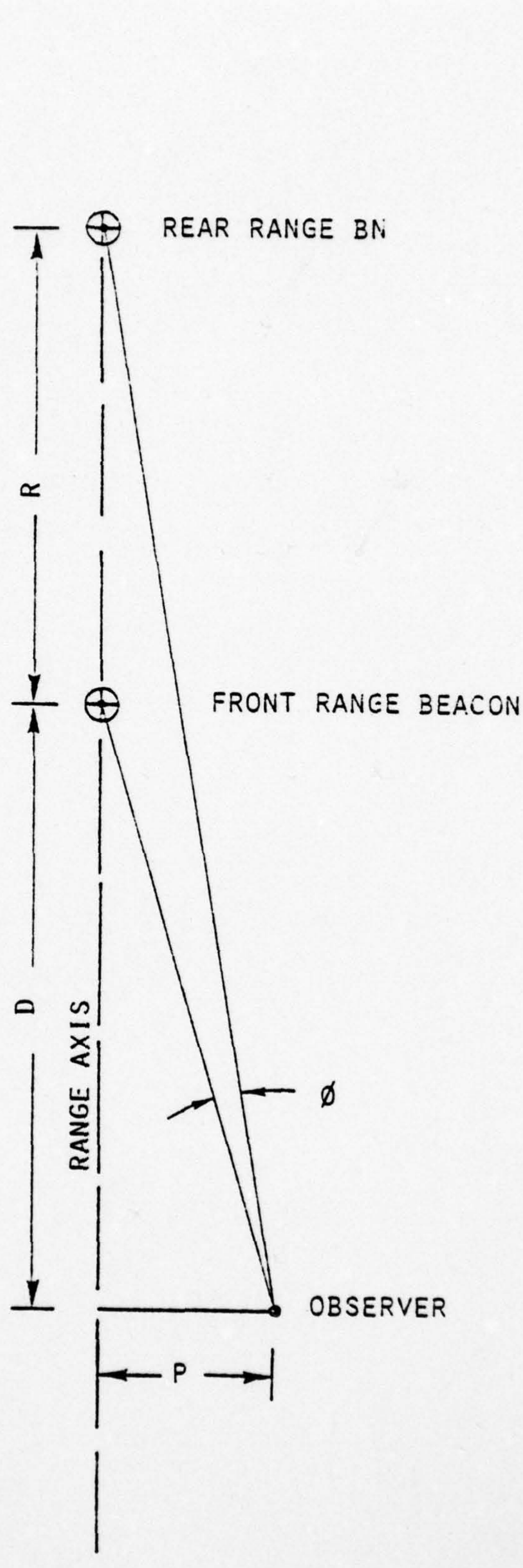

FIGURE B-5. RANGE GEOMETRY

due to uncertainty in the mariner's distance to the range, $\sigma_{\emptyset:D}$. This latter error, of course, is not "real" in the sense that it is not a true uncertainty in the observation of the visual angle. It is simply mapped to the observable from D for convenience in error propagation.

The total error in Ø is:

$$\sigma_T = \sqrt{\sigma_{\emptyset}^2 + \sigma_{\emptyset:D}^2},$$

which is propagated to the navigation variable P in the usual way.

2.3 Considerations for Skewed Distributions

The errors in many of the A/N observables are appropriately characterized by skewed distributions such as, for instance, the log-normal. One example is the observable for ranging, which for a given distance to the range, is the visual angle subtending the front and rear ranges. (A similar example would involve ranging from buoys marking the channel edge.)

Based on consideration of the reference point for ranging, which is the on-range position, the error involved in ranging increases with distance off-range (this was borne out both in the pilot interviews and by our ranging experiment). Further, for estimates involving ranging, this function is probably too strong to approximate the distribution by a normal distribution (the normal distribution requires a constant variance). Figures B-6.a and B-6.b illustrate this situation, in comparison to a case where the normal distribution approximation would be appropriate.

For the edge of channel case, involving ranging as the observable, the relationship between the error in the observable and the observable is approximated by a linear function, i.e.:

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$\sigma_{P_u} \approx \sigma_{P_L}$: Approximate by $\sigma_{P'}$ and assume P is distributed normally with variance $\sigma_{P'}$.

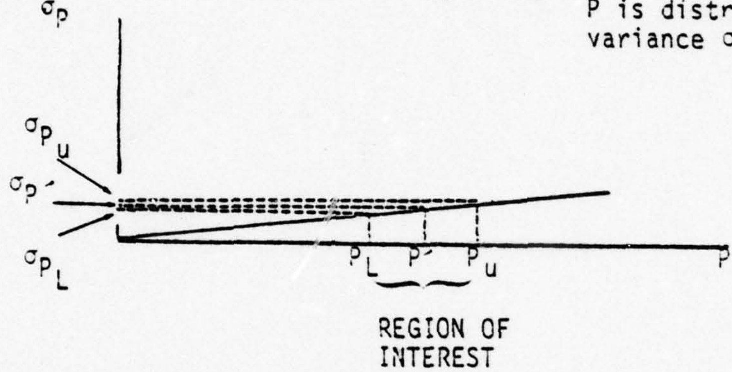

FIGURE B-6.a ERROR IN OBSERVABLE IS A WEAK FUNCTION OF OBSERVABLE.

$\sigma_{\phi_u} >> \sigma_{\phi_L}$: Cannot validly approximate σ_{ϕ_u} and σ_{ϕ_L} by $\sigma_{\phi'}$.

A characterization of the error in the observable ϕ by a lognormal distribution is often adequate.

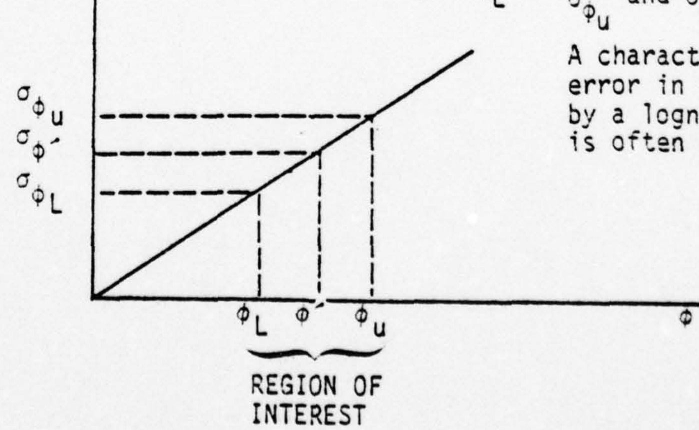

FIGURE B-6.b ERROR IN OBSERVABLE IS A STRONG FUNCTION OF OBSERVABLE.

$$\sigma_{\phi} = K\phi$$

where:

- σ_{ϕ} is the standard deviation of the observable ϕ.
- ϕ is the ranging visual angle observable.
- K is the slope of the straight line representing the relationship between the standard deviation of the observable, and the observable.

If this linear relationship is valid (and our experimental evidence indicates that it is valid), then the lognormal distribution could be a reasonable choice to characterize the error in the visual angle observable. (As a point of comparison, some information on the ability to make direct estimates of distance to an object is available in the human factors literature, and on this basis it was surmised that the normal distribution approximation would adequate characterize this case. Even in this case the error in estimating distance is proportional to distance, but the change appears to be small enough compared to the region of interest for error propagation so that the normal approximation is an adequate characterization of the error.)

For observables characterized by lognormal or other non-normal distributions, the solution technique required to propagate errors from the observable to the navigation variable is slightly more complex than the generalized least squares techniques used for the majority of error propagations in the Phase I program. The generalized least squares technique requires that the observable be normally distributed, and results in a normal distribution for the navigation variable. Because the error in the observable is a strong function of the observable, this is an inappropriate assumption for estimating P by ranging. Therefore, a Monte Carlo solution technique was developed for this purpose.

Figures B-7 and B-8 show the error propagation results for four cases of estimating P from the ranging reference point using this solution technique (distance to the range was assumed to be known). As can be seen, the distributions for P are slightly skewed, indicating the decreased error in estimating P as one moves toward the range reference point (the on-range position, or channel edge).

2.4 Preliminary Considerations for Conventional Ranges

A range provides three elements of information to the mariner:

- A precise reference for on-axis transit.
- An indication of the cross-track position when off the range, and
- An indication of the adequacy of the turning rate when entering the range.

In general, only the first is completely unambiguous to an observer who is not familiar with the particular range. When off the range axis by some distance P, the observed horizontal distance (visual angle) between the range beacons is a function of the ratio of the observer's distance from the front beacon (D) to the distance between the range beacons (R).

Figure B-9 illustrates the range geometry. If the observer is not familiar with the range, he is unlikely to realize the significance of a particular value of ϕ even though he is aware of the values of D and R. When the ratio of D to R is large, even a very small visual angle represents a large off-track ship position. With well designed range beacons, a visual angle of one minute of arc is clearly discernable (the minimum angle discernable has not been determined, and it will be influenced by the vertical separation and the background contrast).

Figure B-10 shows a rather extreme case with a D/R of 10. The geometry is shown in Figure B-10.a. Figure B-10.b shows the appearance

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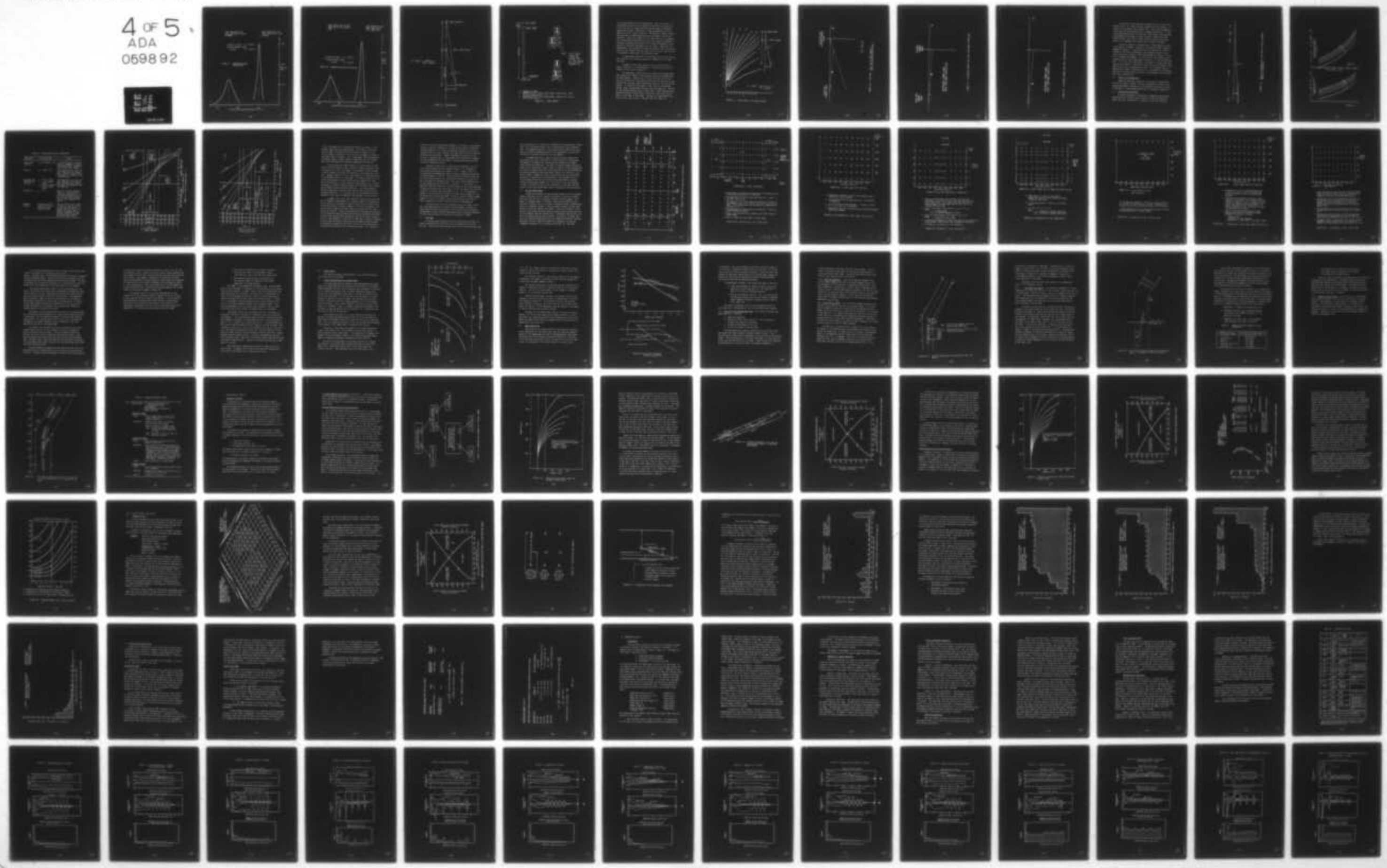

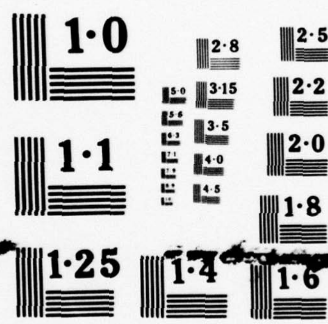

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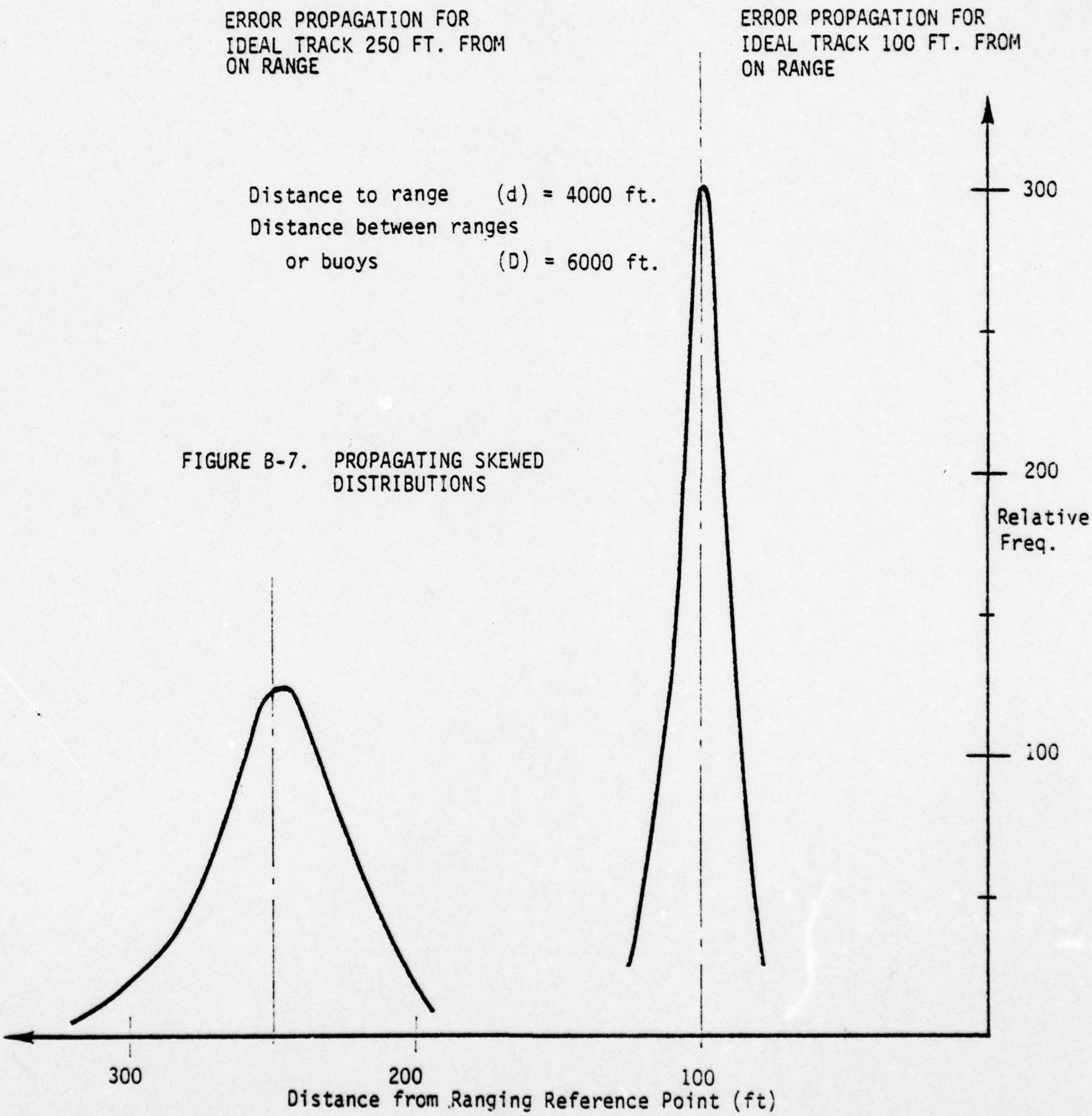

FIGURE B-7. PROPAGATING SKEWED DISTRIBUTIONS

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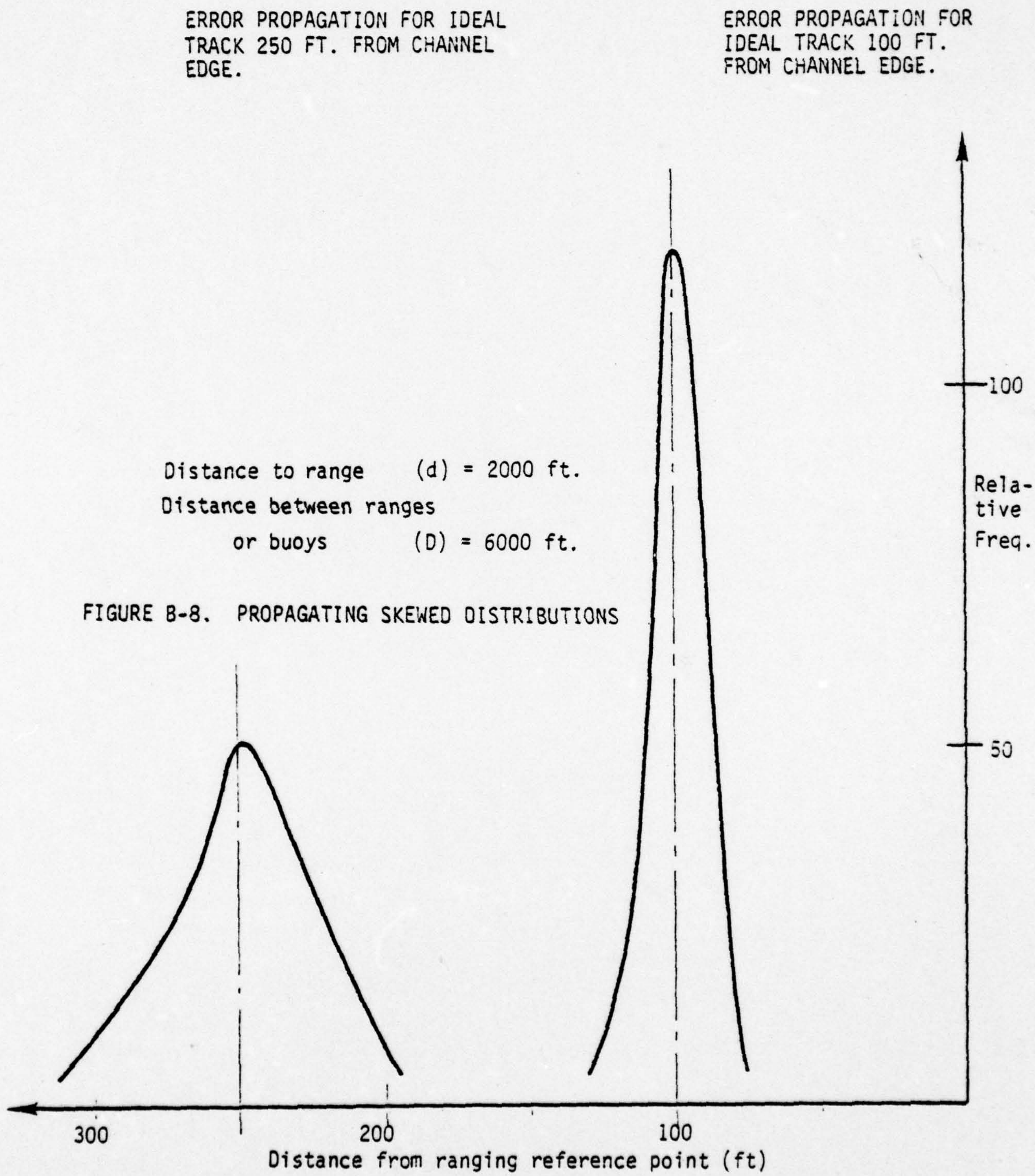

FIGURE B-8. PROPAGATING SKEWED DISTRIBUTIONS

$$\phi = \mathrm{TAN}^{-1} \frac{PR}{PR^{2} + D(D+R)}$$

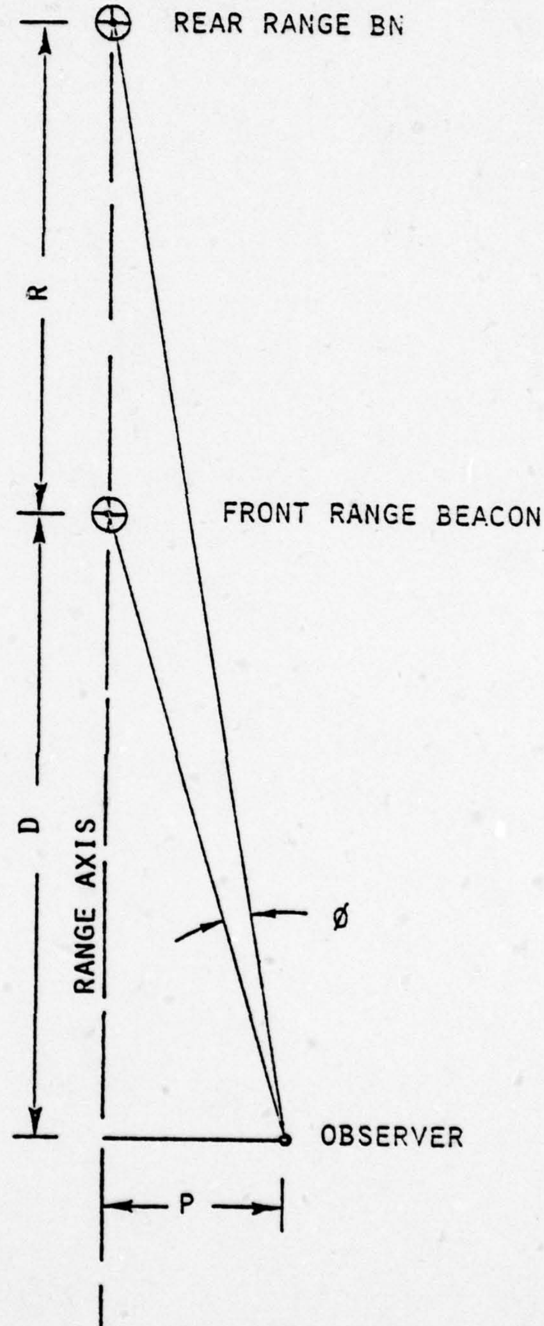

FIGURE B-9. RANGE GEOMETRY

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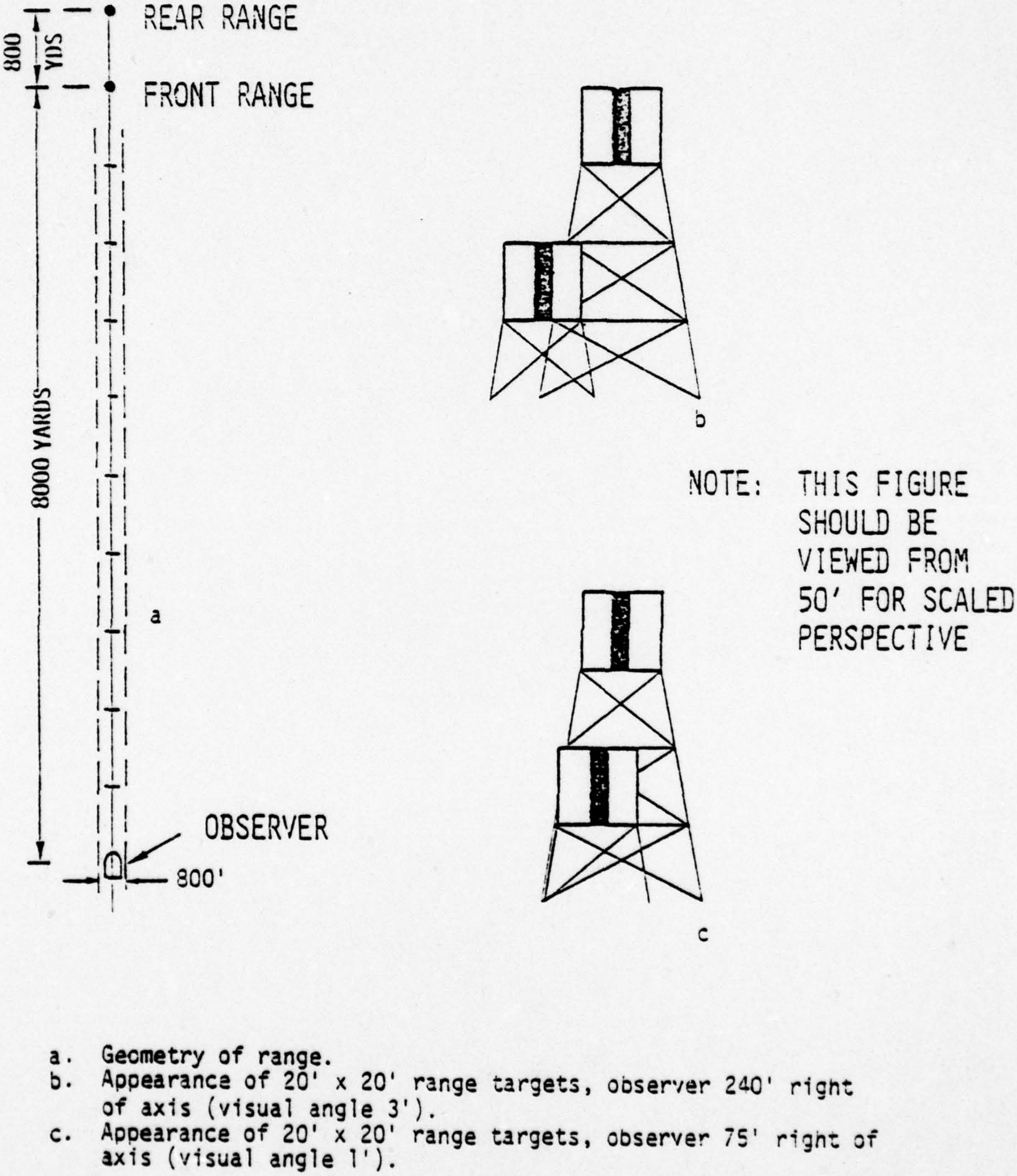

a. Geometry of range.
b. Appearance of 20' x 20' range targets, observer 240' right of axis (visual angle 3').
c. Appearance of 20' x 20' range targets, observer 75' right of axis (visual angle 1').

FIGURE B-10. RANGE GEOMETRY

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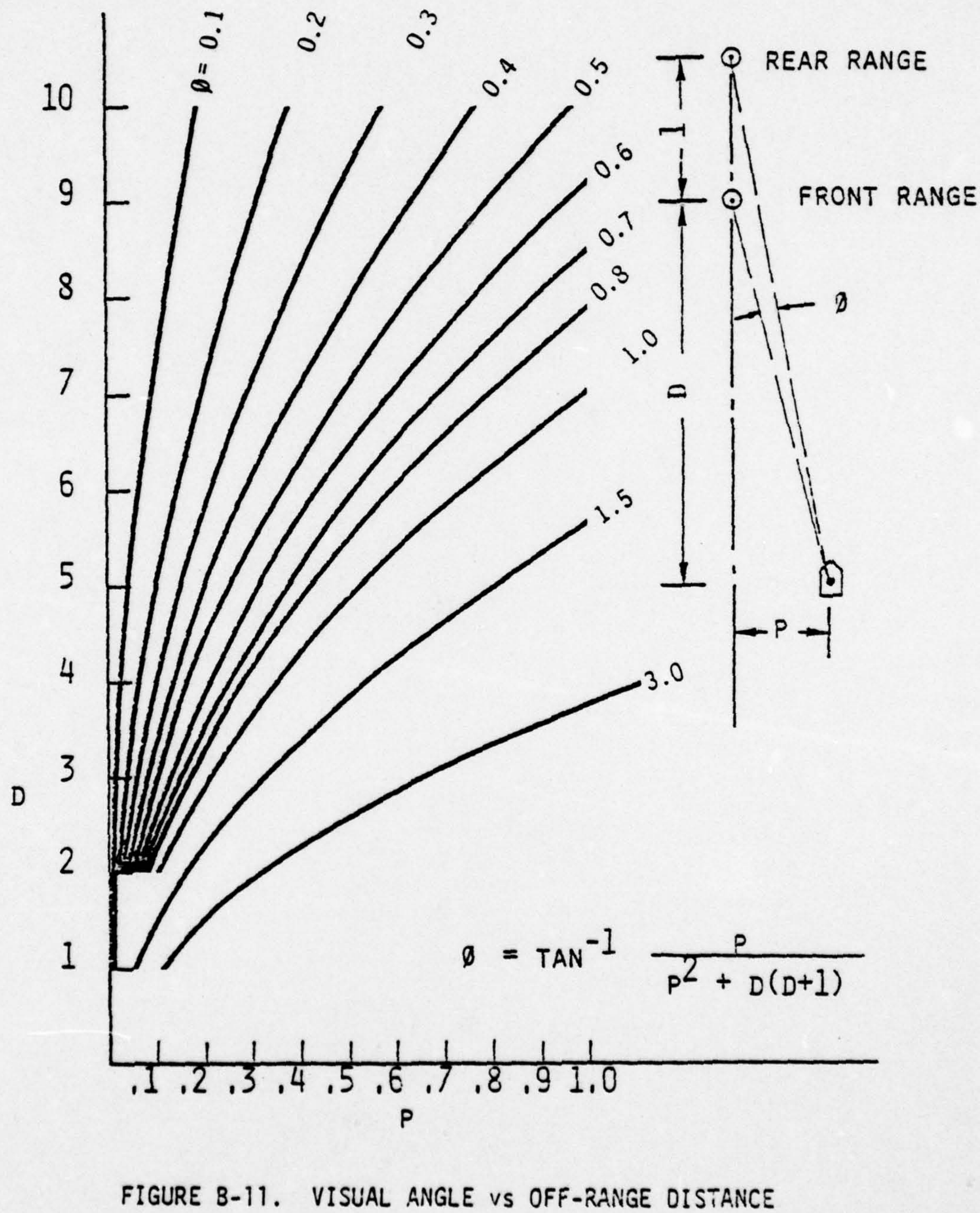
of the range beacons with the observer 240' right of the axis. An experienced observer of this range would know that he was about as far off the axis as prudent when the opposite edges of the beacon panels were aligned. Figure B-10.C shows the appearance with the observer only 75' right of the axis. The opening is clearly discernable and even an unexperienced observer would detect the off-axis condition. Since, for a given P, ø will vary with D, it is apparent that considerable experience with a particular range is necessary to accurately estimate cross-track position from the appearance of the beacons as the vessel progresses along the range. Interviews with experienced pilots indicate that they can ascertain their cross-track position "very closely" when the range is only slightly open and within "hundreds of feet" when it is appreciably open.

A range permits detection of cross-track position very quickly. With a D/R of 5, an off-axis distance of 1 percent of R will open the range 1'.

A summary of the visual angle vs P as a function of D/R is shown in Figure B-11. For convenience, R is taken as unity and all values of P and D are in terms of R.

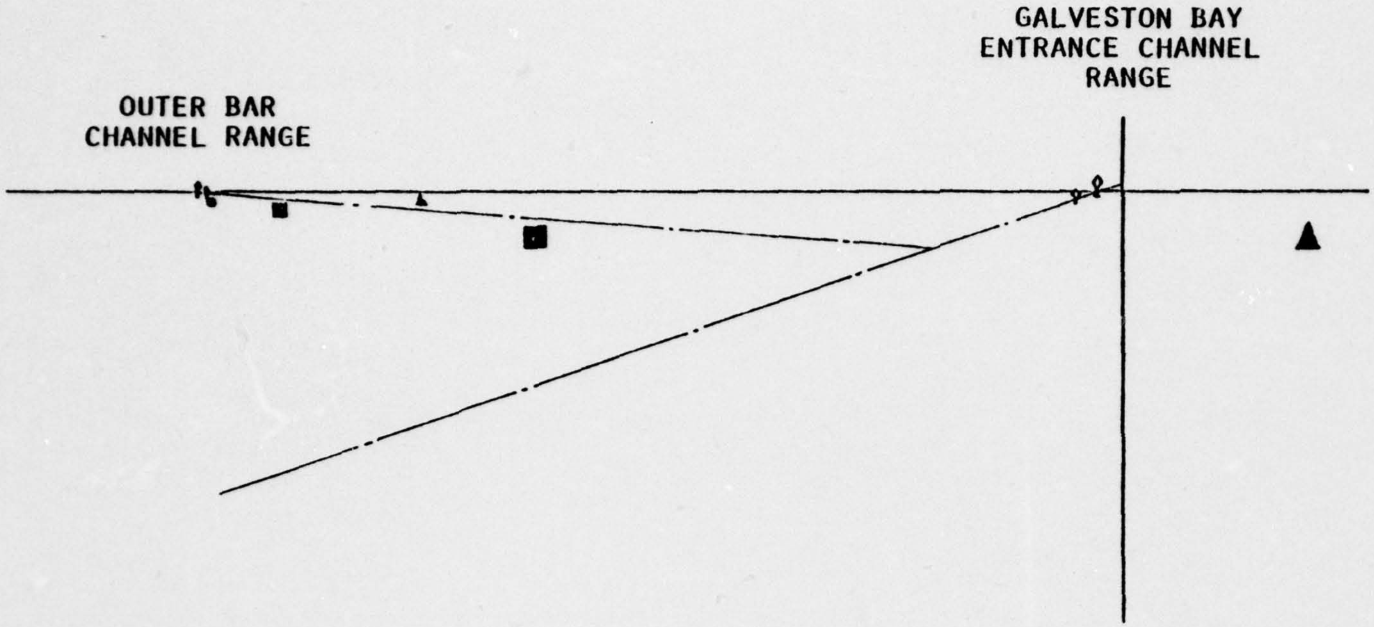
The importance of familiarity with ranges, for purposes other than maintaining a vessel on the range axis, can be illustrated with an actual example. Figures B-12, B-13 and B-14 show the mariner's view of principal aids to navigation as he nears the inner end of the Galveston Bay entrance channel approaching the turn into the Outer Bar channel. In Figure B-12 the vessel is 200' right of the entrance channel range, and about 850' from the outer bar range axis. The D/R for the entrance channel range is nearly unity, hence the beacons are opened considerably (visual angle of about 25") even though the observer is only 200' off the range. The outer bar range beacons present a visual angle of only 11' because the D/R is about 6.7.



$$\emptyset = \tan^{-1} \frac{P}{P^2 + D(D+1)}$$

FIGURE B-11. VISUAL ANGLE vs OFF-RANGE DISTANCE

(300)



23" FROM EYE

FIGURE B-12. VIEW FROM - 200' R of CL (800' CHANNEL)
3000' FROM INTERSECTION OF RANGES

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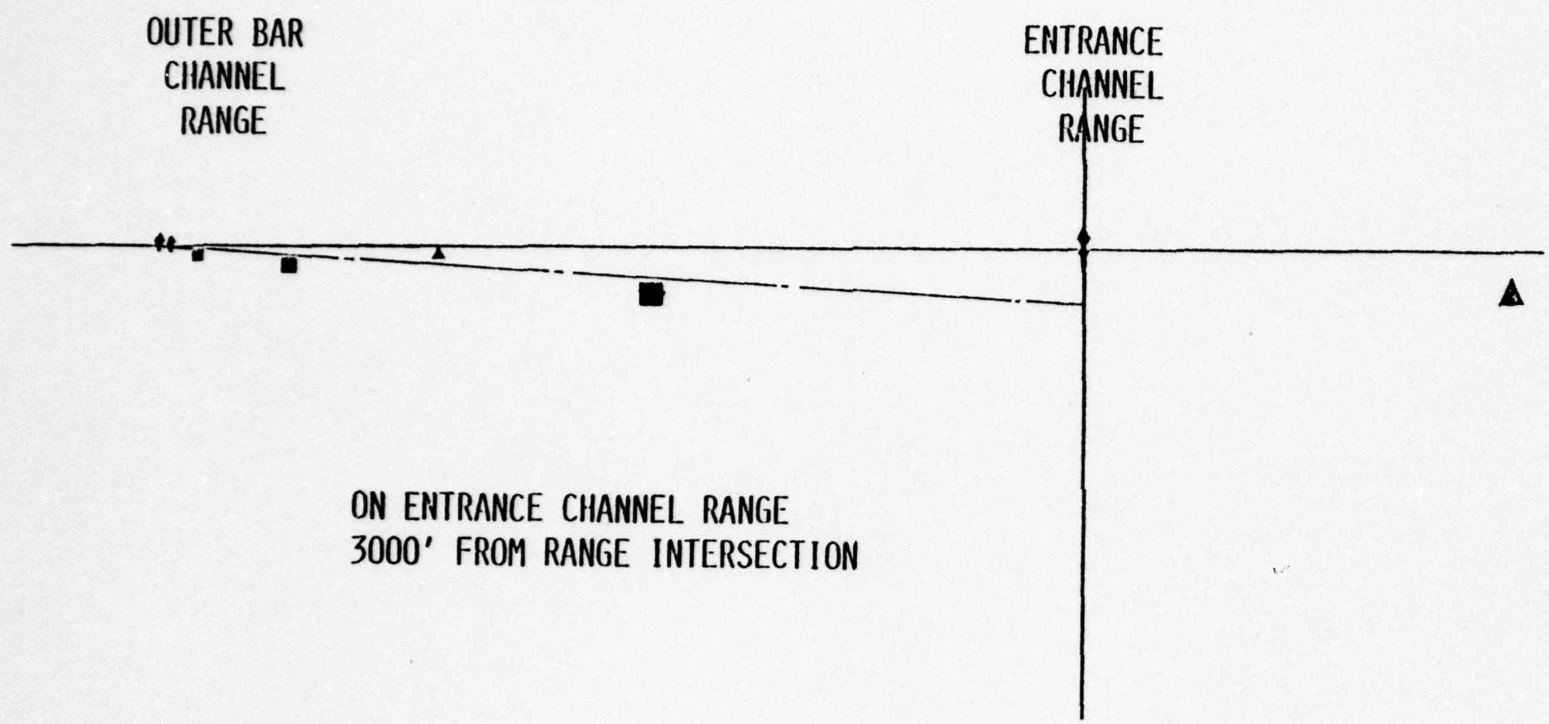

FIGURE B-13. ON ENTRANCE CHANNEL RANGE 3000' FROM RANGE INTERSECTION

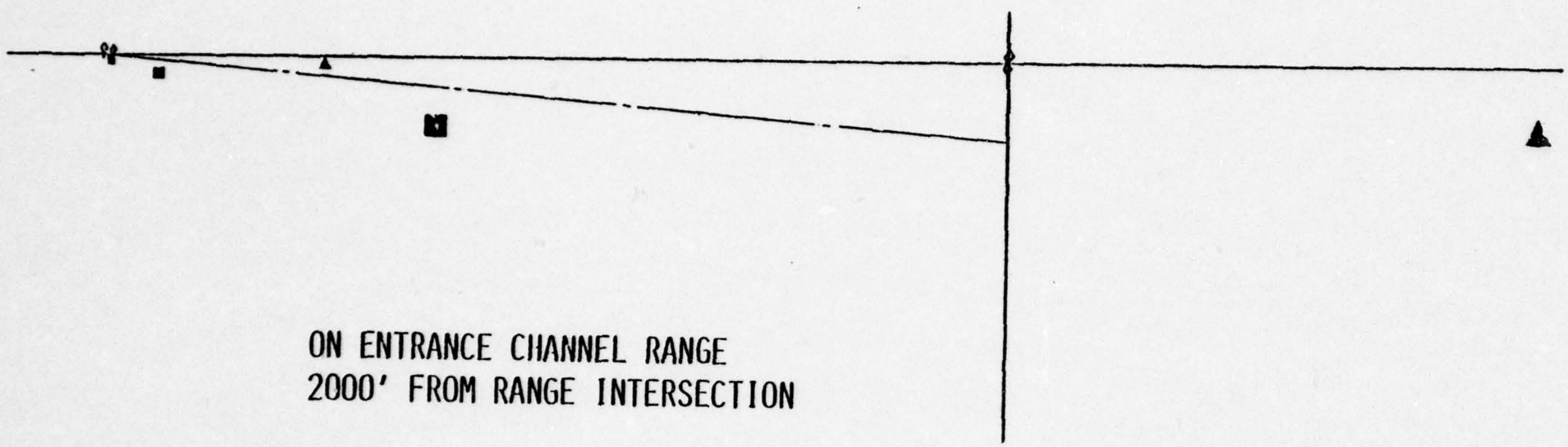

FIGURE B-14. ON ENTRANCE CHANNEL RANGE 2000' FROM RANGE INTERSECTION

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In Figure B-13 we have placed the observer back on the entrance channel range. He is 3000' from the intersection of the ranges. In Figure B-14 the observer has advanced 1000'. Note that the appearance of the outer bar range beacons has not changed significantly. If the vessel were approaching at 15 knots, the visual angle of the outer bar range beacons would change at a rate of about 7 minutes of arc per minute of time. This rate of change is equal to that of the minute hand on a 12" diameter clock viewed from a distance of 26 feet.

The subtle changes in the appearance of range beacons are best illustrated by an example. Consider a range having a 3000' separation between the beacons. A vessel desiring to run parallel to, at some distance P from the axis (perhaps to clear meeting traffic), would view a continuously changing visual angle between the beacons. Figure B-15 illustrates the geometry. In Figure B-16.a, the visual angle vs. distance from the front range beacon is shown for P = 100, 200, 300 and 400'. If P = 200, the visual angle is only about 12' when 12,000 feet from the front beacon. Figure B-16.b shows the rate of change of visual angle from a vessel proceeding at 10 knots. It is apparent that an observer would require exceptional ability to ascertain his cross-track position or to sense a rate of change in that parameter from the appearance of the range beacons.

2.5 Errors in A/N Observables

Table B-2 summarizes the errors in the visual A/N observables used for the Phase I program. The error propagation resulting in the σ_p maps was based on these errors. The source for the errors is given in the table. A more complete description is provided in Appendix A.

3.0 Direction of Ship Motion

An initial hypothesis in the Phase I program was that mariners might be able to fix their ship's direction of motion by detecting motion real-time, using the A/N. Figures B-17 and B-18 illustrate

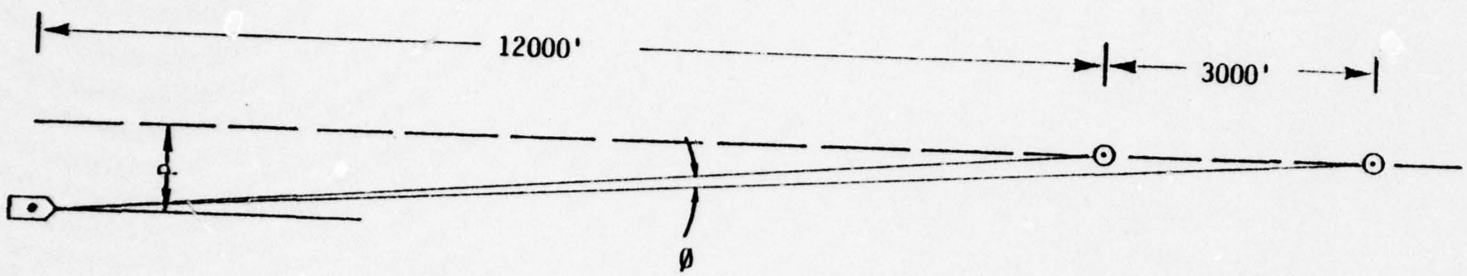

FIGURE B-15. EXAMPLE OF APPEARANCE OF VISUAL ANGLE FOR VESSEL RUNNING PARALLEL TO RANGE AXIS

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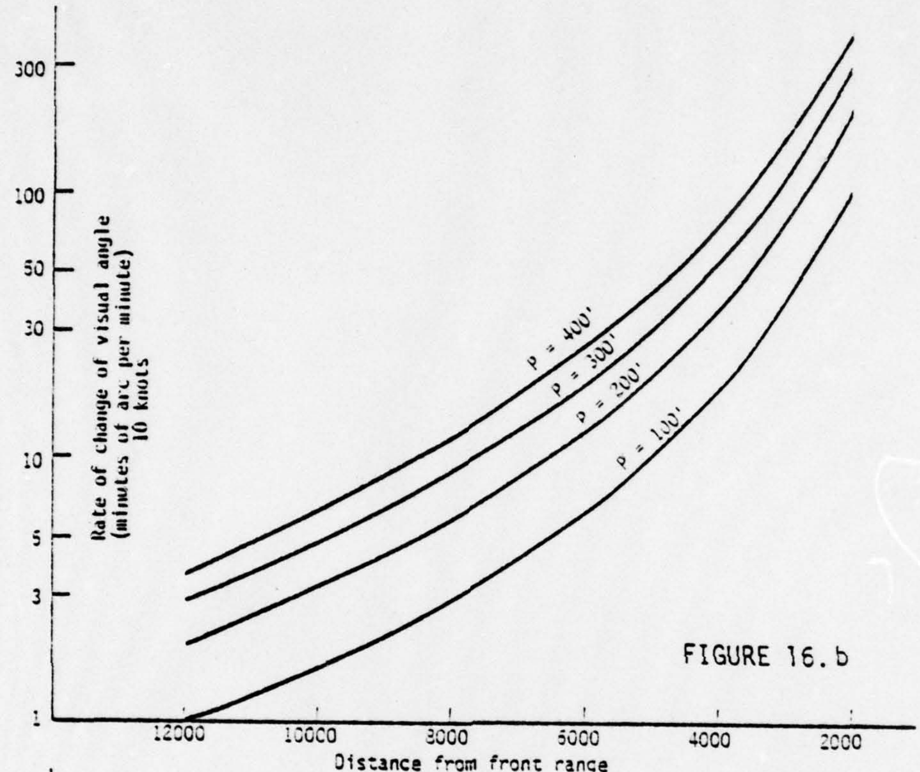

FIGURE 16. b

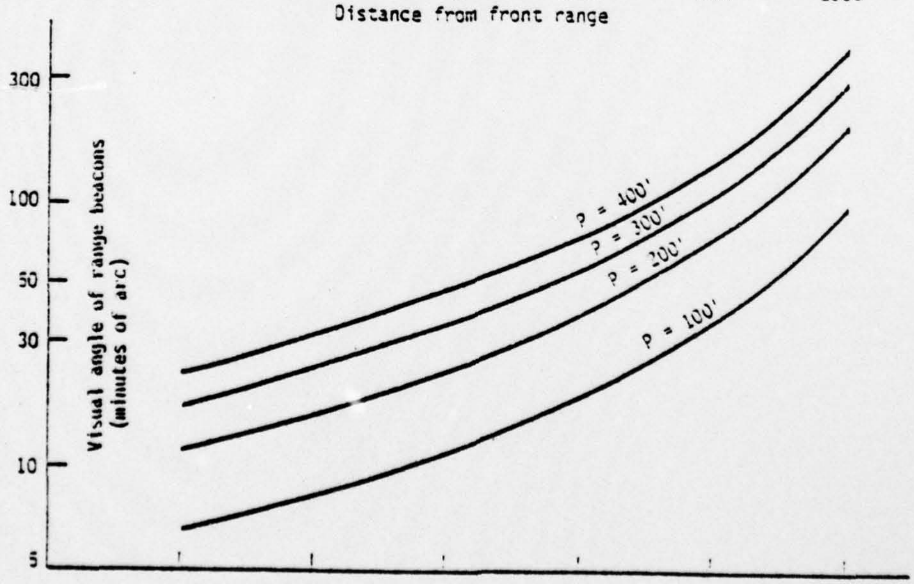

FIGURE 16. a

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TABLE B-2. ERROR ASSOCIATED WITH OBSERVABLES

Observable	Error Equations	Source
Visual angle ratio (R)	$\sigma_R = (.5\lvert\log R\rvert + .1)R$	J. Baird's analysis of experiments on judgments of size in the frontal plane. Nonoptimal viewing conditions assumed.
Slope (S)	$\sigma_S = .054\,S + .015$	Least-squares fit to data from our range sensitivity experiment. Equation should require adjustment for nonoptimal viewing conditions.
Horizontal component of visual angle	$\sigma_\phi = .054\,\phi + .010\,V + .21$ minutes, where V = vertical component of visual angle	Least squares fit to data from our range sensitivity experiment. Equation should require adjustment for nonoptimal viewing conditions.
Distance (D)	$\sigma_D = .1\,D$	Good fit to Worley & Markley (1969) for large distances estimated on the basis of visual angle subtended by an object of known size, adjusted to allow for nonoptimal conditions.
Change of bearing	No error equation; threshold = .3 minutes of arc per second of time	Harvey & Michon (1974), based on motion of objects toward or away from each other. Although small for that kind of motion (4 seconds viewing allowed), threshold is probably too large for objects moving past each other.

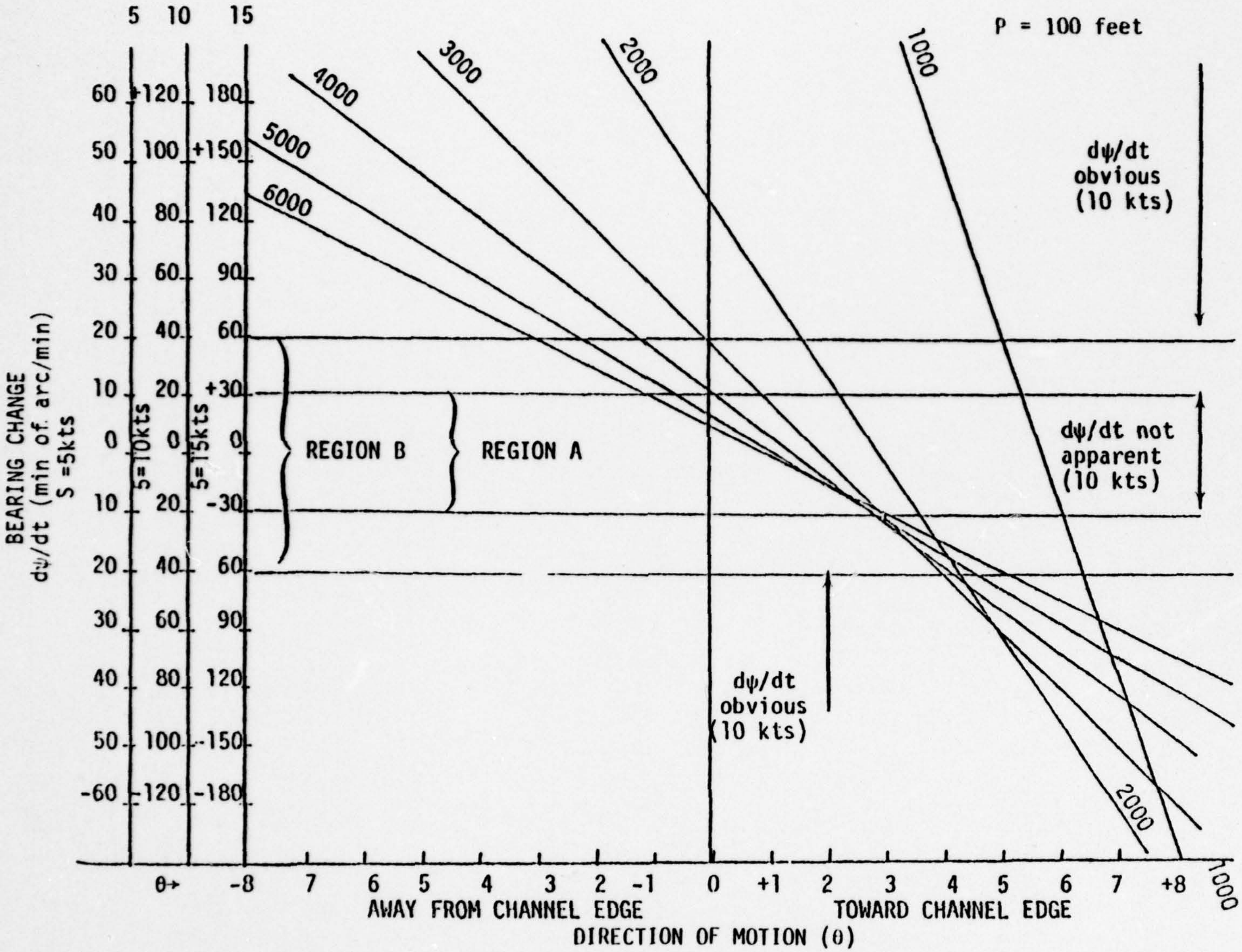

FIGURE B-17. RATE OF BEARING CHANGE vs θ

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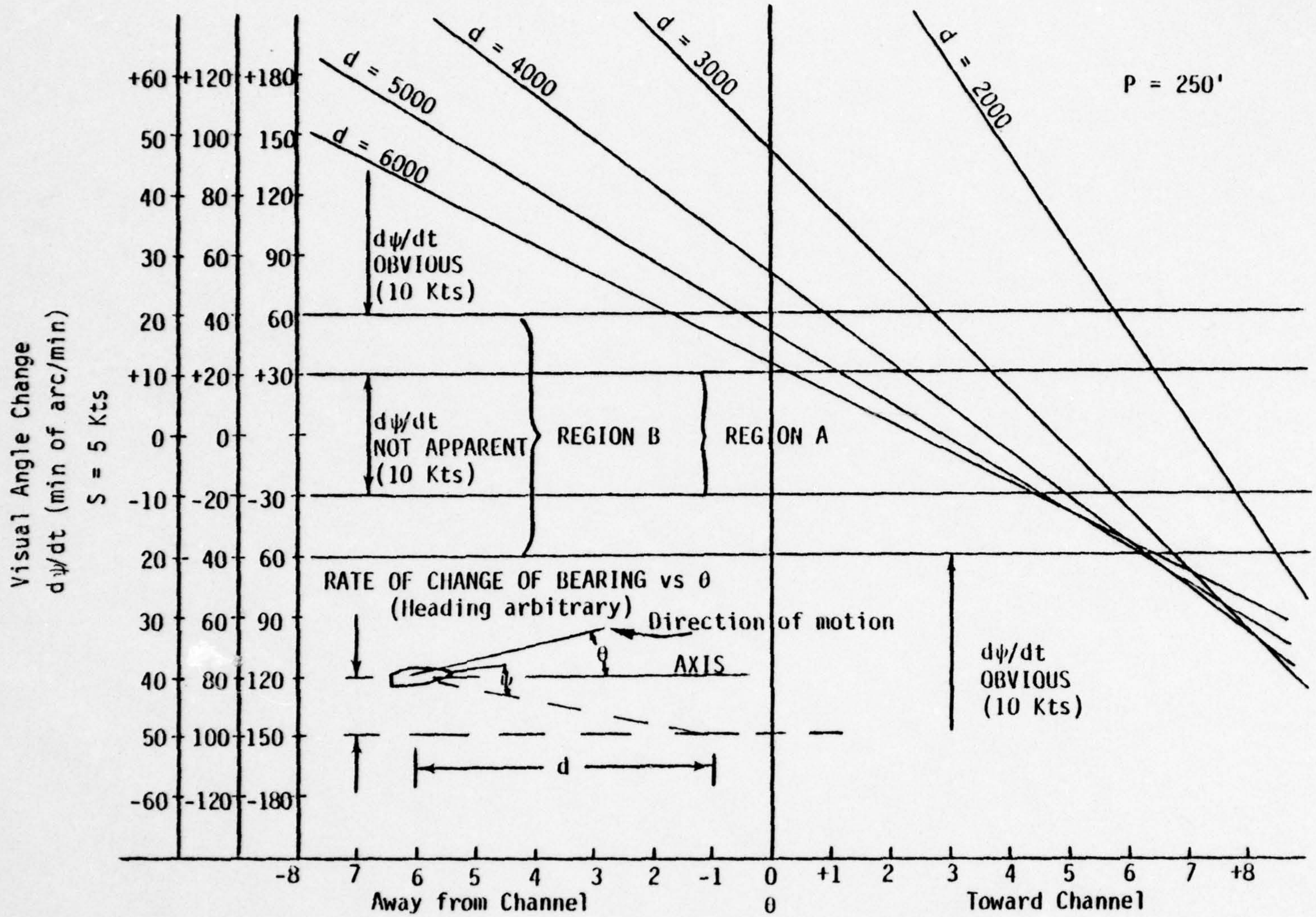

FIGURE B-18. RATE OF BEARING CHANGE vs θ

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initial considerations for estimating direction of motion, θ, from changes in bearing to the nearest buoy. The change in bearing observable, $\frac{d\psi}{dt}$, is plotted versus the direction of motion, θ, for various values of distance to the first buoy, d (speed is 10 knots). The dotted lines illustrate: (a), a region where real-time detection of bearing change is almost certainly impossible, and (b) a region where real-time detection of bearing change would be difficult.

As can be seen from these figures, for large values of d the mariner would not expect to see a real-time change of bearing to the first buoy at a 10 knot ship speed; if he observed a bearing change, it would indicate to him that his direction of ship motion was incorrect. However, there is a fairly large spread for θ that would result in no detectable motion (in real-time). For smaller values of d, the mariner would expect to see a positive bearing change if his ship motion direction was, in fact, parallel to the channel axis. No bearing change, or negative bearing change, would indicate a ship's motion vector toward the near grounding constraint. Too large a positive bearing change would indicate a ship's motion vector toward the far grounding constraint. It is evident that the distribution of the observable in this case will depend on the distance to the first buoy.

It appears that fixing ship direction of motion using real-time rate of change of observables (i.e., change of bearing to a buoy) may be too difficult a psychological task to constitute the primary means of setting direction of motion, especially for slow ship speeds. However, pilots do report that under certain conditions they can "see" direction of motion. We are at the present time viewing the utilization of this observable more as establishing bounds on acceptable directions of motion than as the primary process for setting direction of motion. That is, the information is available in many cases to detect directions of motion that are grossly wrong; but the information does not appear to be sensitive enough for the pilot to rely on as the primary means of establishing and setting his navigation variable. For instance, if

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bearing to a buoy on the bow were detected to be moving in the opposite direction from that expected; or if there were no bearing change when one was expected; or if a bearing change was detected when none was expected, the pilot would realize "real time" that his ship's direction of motion was not correct. However, reference to Figures B-17 and B-18 will illustrate that, in many cases, this information is probably not precise enough to be the primary variable permitting the mariner to set his direction of motion.

Figure B-17 shows that if the mariner were 6000 feet from the buoy, he would expect to see no bearing change if his direction of motion were straight down the channel ($\theta = 0$). However, region A, corresponding to nondetectable bearing changes, encompasses directions of motion between -1^{o} and $+3^{o}$. Thus, he could be traveling toward the near grounding constraint with a direction of motion of as much as 3^{o} and not be able to distinguish this (real time) from the desired case of zero degrees direction of motion. Similarly, if the mariner is 2000 feet from the closest buoy, he would expect to see a bearing change of about 82 minutes of arc per minute, at a 10 knot speed if his direction of motion is straight down the channel ($\theta = 0$). It is problematical whether or not he could distinguish this from a bearing change of, say, 60 minutes of arc per minute, which is also an "obvious" bearing change, especially since it is doubtful that he would have an error-free internal expectation concerning what the bearing change should be.

A tentative conclusion from arguments such as the above is that real time observables for direction of motion probably indicate in a broad sense when direction of motion is not correct, but are probably supplemented by other navigation techniques such as successive estimates of cross-track position, for setting ship direction of motion.

4.0 Error Maps

A straight channel marked with an A/N system can be divided into zones characterized by a particular error in estimating cross-track position. The error for each zone may result from a particular observable

that the mariner uses in that zone, or because the zone represents a region that is at a different distance from a reference point than an adjacent zone. The standard deviations in cross-track position shown on the error map are obtained by propagating errors in the observables to cross-track positions, as discussed in Section 2 of this Appendix.

An example error map is shown in Figure B-19 that relates pilot uncertainty of his ship's position to various locations in the waterway. The example illustrates pilot uncertainty while traveling a straight channel marked by gated buoys. The center of channel (roughly 300 feet to either side of the channel center) errors on Figure B-19 were computed from the center of channel observables (angle matching) using the experimentally derived angle matching errors described in Section 2.5, Table B-2. The edge of channel, between-buoy errors were derived using the relationship of Section 2.2 where slope is the observable (K was assumed to be 0.1). The buoy-abeam zone errors were derived using experimentally obtained distance estimate data (Appendix A). Error maps for the cases analyzed in Phase I are shown in Figures B-20 through B-26. These error maps are input to the run and observe model which is discussed in the next section.

5.0 Run and Observe Model

A model was developed for the navigation process of run and observe, whereby the mariner sets his direction of motion by a series of fixes on cross-track position as he navigates a channel or harbor complex. This model is a capstone model in our Phase I human factors modeling effort. The model is based on the run and observe navigation process, whereby ship's motion in navigating a channel is set by successive checks of cross-track position as the ship traverses the channel. Cross-track position is corrected to the desired value when these successive checks indicate that the ship has wandered from the intended track. Information from the A/N is the basis for determining cross-track position. Our analysis indicates that the run and observe process may be a basic navigation process for confined waterways; the pilot interviews support this contention, as does the independent assessment of our navigation consultant, Dr. John Kemp.

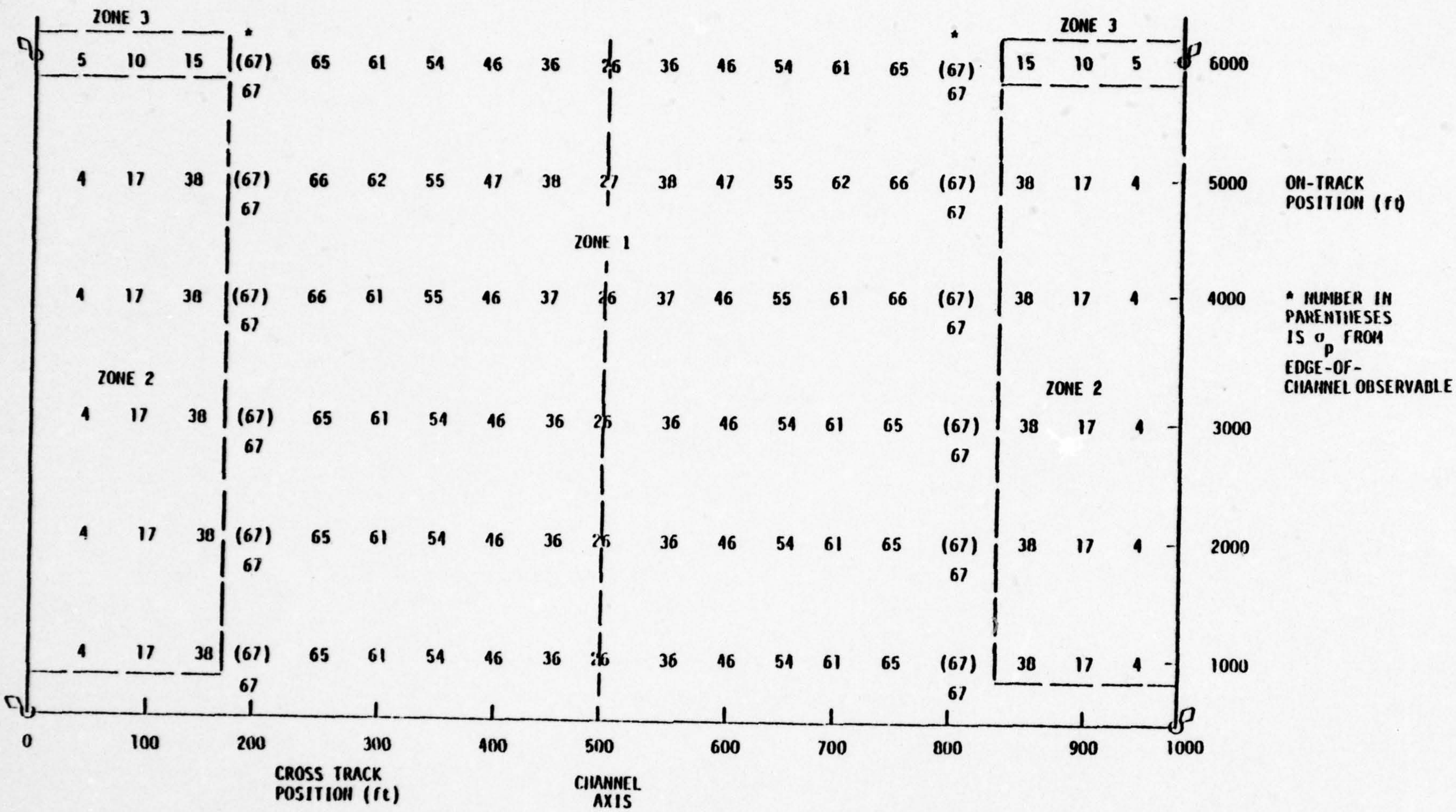

FIGURE B-19. EXAMPLE OF ERROR MAP (Straight Channel, Gated Buoys)

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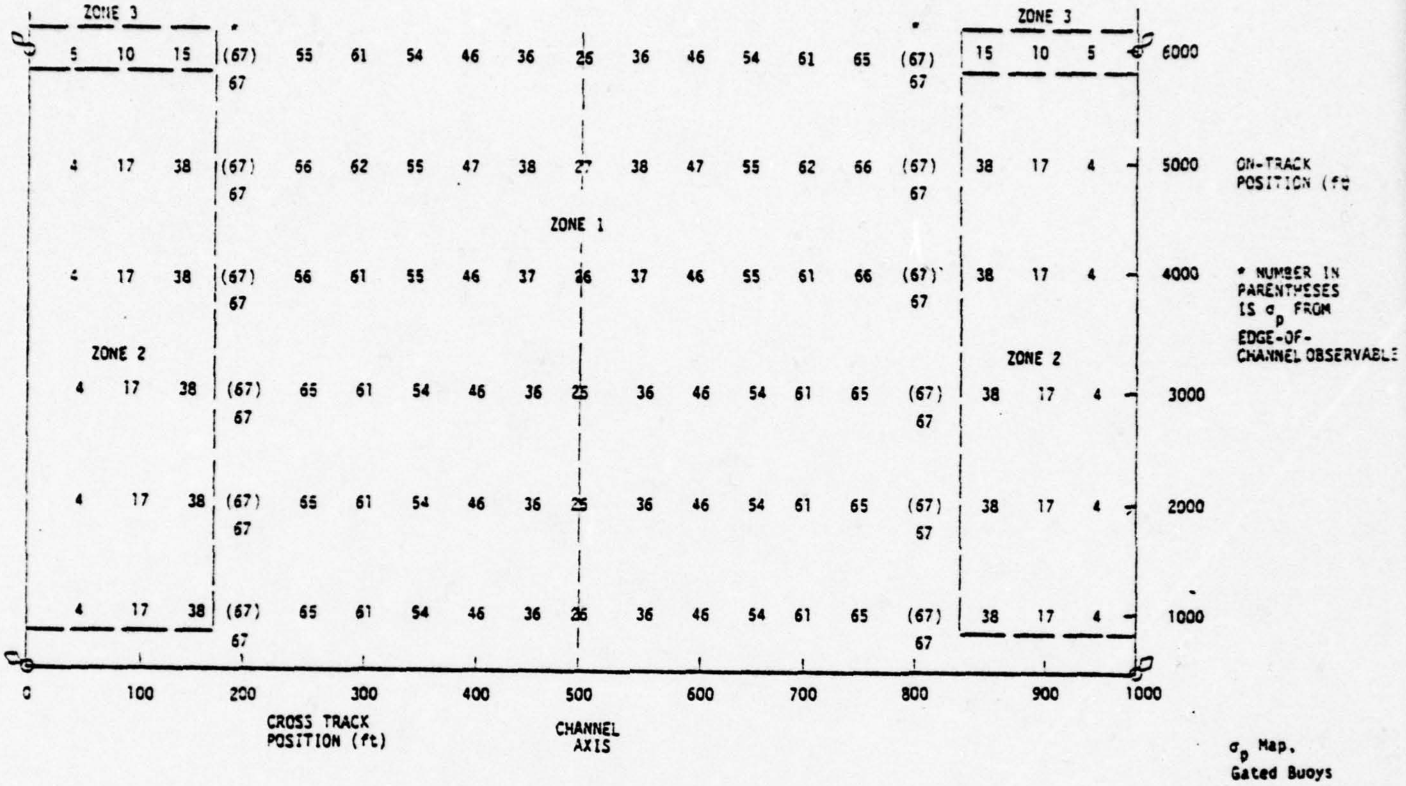

FIGURE B-20.a σ_p MAP, GATED BUOYS.

- Three zones are displayed corresponding to the observable for fixing cross-track position in the zone.
- The observable for fixing cross-track position in Zone 1 is matching visual angles.
- The observable for fixing cross-track position in Zone 2 is the apparent slope of the line of buoys marking the channel edge. Fixing cross-track position using this observable is discussed in B.I. 2.
- The observable for fixing cross-track position in Zone 3 is direct distance estimation.
- Zones 1 and 2 are arbitrarily meshed at 200 feet from each channel edge.
- Zone 3 is used only when there is a buoy abeam.

FIGURE B-20.b DISCUSSION OF σ_p MAP, GATED BUOYS.

87 1/2 0/0 314

ON TRACK POSITION (FT.)	100	200	300	400	500	600	700	800	900
6000	10	20	30	40	50	60	70	80	90
5000	17	67	150	267	417	600	817	1067	1350
4000	17	67	150	267	417	600	817	1067	1350
3000	17	67	150	267	417	600	817	1067	1350
2000	17	67	150	267	417	600	817	1067	1350
1000	17	67	150	267	417	600	817	1067	1350
0	10	20	30	40	50	60	70	80	90

CROSS-TRACK POSITION (FT.)

FIGURE B-21.a σ_p MAP, BUOYS LEFT SIDE ONLY.

- Observable is apparent slope of line formed by bouys lining left side of channel.
- Error equation relating observable and P are reported in Appendix B.
- σ_p's are height-of-eye dependent. A height of eye of 60 ft. was used for this example.
- Cross-track position fixed by direct distance estimation when buoy is abeam.

FIGURE B-21.b DISCUSSION OF σ_p MAP, BUOYS LEFT SIDE ONLY.

— REAR RANGE

— FRONT RANGE

		100	200	300	400		500		600	700	800	900		NAUTICAL MILES
	92	73	55	37	19	10	2	10	19	37	55	73	92	1
	100	81	61	42	23	13	5	13	23	42	61	81	100	2
ON TRACK POSITION (N. MI.)	107	86	66	47	27	18	11	18	27	47	66	86	107	3
	113	92	72	52	33	24	18	24	33	52	72	92	113	4
	119	99	79	59	41	33	27	33	41	59	79	99	119	5
	127	107	87	68	51	43	37	43	51	68	87	107	127	6

CROSS-TRACK POSITION (FT.)

FIGURE B-22.a σ_p MAP, RANGE CASE #1 (RANGE ONLY).

- Error in fixing cross-track position (σ_p) due to two components: (1) error in fixing cross-track position from a given horizontal visual angle, given the observer is a known distance from the range; and (2) error in fixing distance from the range.
- Error in horizontal visual angle is: $\sigma_\phi = 0.5' + 0.1\phi$
  where
  ϕ = visual angle
  0.5 is constant component of error.
- Error in fixing distance from range is: $\sigma_D = 0.1 D$.
  where
  D = distance to front range.
- σ_ϕ and σ_D are propagated to cross-track position to obtain σ_p's, using standard least squares error propagation techniques.
- On range σ_p's are due only to 0.5′ ambiguity.

FIGURE B-22.b DISCUSSION OF σ_p MAP, RANGE CASE #1.

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— REAR RANGE

— FRONT RANGE

(σ_p in feet)

		100	200	300	400		500		600	700	800	900		NAUTICAL MILES
	52	42	32	22	12	7	2	7	12	22	32	42	52	1
	60	48	37	26	14	9	3	9	14	26	37	48	60	1.5
	55	45	35	25	15	10	5	10	15	25	35	45	55	2
ON TRACK POSITION (N. MI. FROM FRONT RANGE)	61	51	41	31	21	16	11	16	21	31	41	51	61	3
	68	58	48	38	28	23	18	23	28	38	48	58	68	4
	77	67	57	47	37	32	27	32	37	47	57	67	77	5
	82	72	62	52	42	37	32	37	42	52	62	72	82	5.5
	87	77	67	57	47	42	37	42	47	57	67	77	87	6

CROSS TRACK POSITION (FT.)

FIGURE B-23.a σ_p MAP, RANGE CASE #2, RANGE PLUS BUOYS ONE SIDE

- Range case #2 is same as range case #1 except that buoys are used to better estimate distance to the range.
- σ_ϕ for range case #2 is same as σ_ϕ for range case #1.
- σ_D = min. $\{0.1\ d_i;\ 0.1\ d_{i-1}\}$

  where:

  d_i = distance to nearest ahead buoy.

  d_{i-1} = distance to nearest astern buoy.

FIGURE B-23.b DISCUSSION OF σ_p MAP, RANGE CASE #2

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(317)

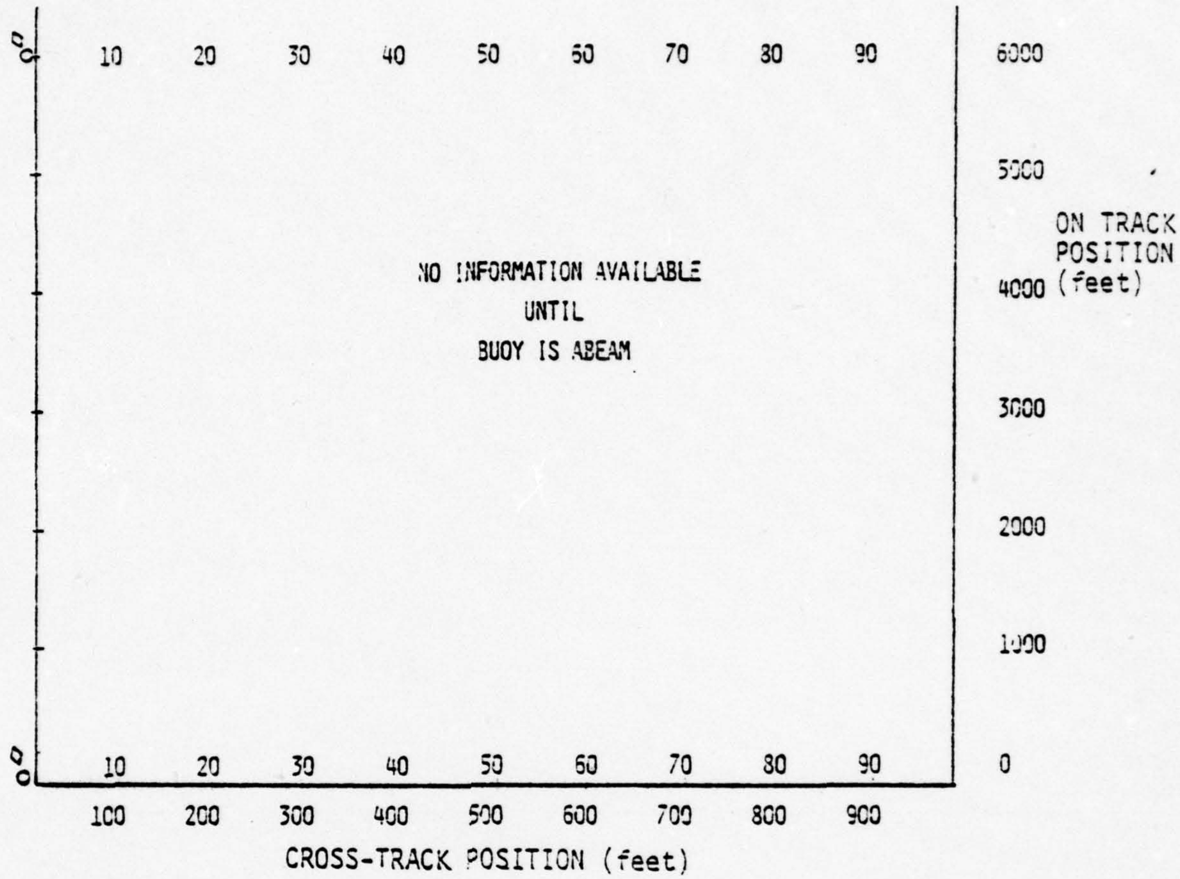

FIGURE B-24.a. σ_p Map; Buoys One Side, Poor Visibility

- Two zones are displayed. Visibility is such that buoys are visible only when the buoy is abeam. Between buoys, no buoys are visible and the mariner has no A/N information.

- The observable for fixing cross-track position is direct distance estimation to the buoy abeam.

FIGURE B-24.b Discussion for Poor Visibility Case.

15%

ON TRACK POSITION (FT)	100	200	300	400	500	600	700	800	900	1000
6000	15	16	18	18	17	17	17	17	18	18
5000	10	20	30	40	50	60	70	80	90	100
4000	10	20	30	40	50	60	70	80	90	100
3000	10	20	30	40	50	60	70	80	90	100
2000	10	20	30	40	50	60	70	80	90	100
1000	10	20	30	40	50	60	70	80	90	100
	15	16	18	18	17	17	17	17	18	18

CROSS-TRACK POSITION (FT.)

FIGURE B-25.a σ_p MAP: RADAR, BUOYS LEFT SIDE ONLY.

- Contributor to error in region between buoys is ability to align cursor on PPI scope and estimate distance to side of channel marked by buoys.
- Timing errors and bearing errors do not substantially contribute in this region, since the effects of timing errors is to lengthen or foreshorten the apparent channel displayed on the screen, and the effect of bearing error is to rotate the apparent channel marked by the buoys and displayed on the screen.
- Errors in the region where there is a buoy abeam are due to errors affecting directed estimate of distance to the buoy:
  - timing errors;
  - resolution of range read-out,
  - correction of slant range to horizontal range.

FIGURE B-25.b DISCUSSION OF σ_p MAP; RADAR, BUOYS LEFT SIDE ONLY.

ON TRACK POSITION (feet)	100	200	300	400	500	600	700	800	900
5000	74	74	74	74	74	74	74	74	74
5000	74	74	74	74	74	74	74	74	74
4000	74	74	74	74	74	74	74	74	74
3000	74	74	74	74	74	74	74	74	74
2000	74	74	74	74	74	74	74	74	74
1000	74	74	74	74	74	74	74	74	74
0	74	74	74	74	74	74	74	74	74

CROSS-TRACK POSITION (feet)

FIGURE B-26.a σ_p MAP: LORAN-C

- It was assumed that the mariners would not transit the waterway using Loran information alone unless he had knowledge that the "fixed" errors (due to survey, approximation in calculation propagation velocities, etc.) has been compensated for.

- The mean square radial error was determined by calculating the error gradient, using the coordinates of the actual LORAN stations, and the time difference error as the RMS value of the time differences due to nominal values for transmitting system instabilities, receiver instabilities and errors, and atmosphere noise.

- Only one component of the error (cross-track) was of interest. This was approximated as the mean square radial error divided by $\sqrt{2}$.

- The result was an error gradient of 1.08 feet per nano-second and an RMS time difference error of 97 nsec. The RMS error for the cross-track component was taken as $(97 \times 1.08) / \sqrt{2} = 74'$.

- The phase II model will compute the N-S and E-W error components separately to define the error elipse. The cross-track component can then be extracted for any given channel course line.

FIGURE B-26.b. DISCUSSION OF σ_p MAP: LORAN C CASE

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The run and observe model was built as a control theory model, where control is provided by the information from the A/N systems. The model uses a finite difference solution technique to accomplish the run and observe process. Statistics reflecting the uncertainty in the information from the A/N are handled explicitly within the model. The input to the model is a σ_p map which describes, for a particular set of A/N, the mariner's ability to establish a cross-track position in the channel.

The run and observe model (Phase I) did not incorporate real ship motion. Ship motion during Phase I was approximated by changing the direction of motion of the ship instantaneously such that the vessel would return to a position nearer to the pilot's desired track. The assumption made in the Phase I model was the pilot would improve his direction of motion when he returned to a postion near his desired track. The Phase I run and observe model provides only comparative risks for various A/N systems, and should not be viewed as risk associated with traveling a waterway marked by a particular A/N system.

The Phase II run and observe model ship motion will be characterized by a ship maneuver model developed by Dr. Harouzo Eda of Stevens Institute of Technology. This ship maneuver submodel will consider such things as rudder angle, drift, velocity vector, rate of turn, etc. The results of the model will be greatly enhanced by the incorporation of real ship maneuvering into the run and observe model.

The outputs from the model are joint distributions of cross-track position error and error in ship's direction of motion, displayed at regular intervals along the channel. These distributions reflect the mariner's ability to use the information from the A/N to steer a course down the channel while maintaining a specified distance from the channel edge. The model clearly shows both transients due to mariner's correcting for unanticipated wind/current conditions, and the steady state after these corrections have taken place.

The model operates by segmenting a distribution of ships into a P-θ space where P and θ are respectively cross-track positions and directions of motion. The model retains the frequency of vessel cross-track positions

in 10 foot cells and the directions of motion in cells of size .4°. The distribution of ships is moved in 300 foot intervals before reapportioning the frequency of ships due to course corrections and motion during the 300 foot interval. Each segment is examined at a succession of distance steps, and the portion of the distribution in each segment that recognizes that they are not at the correct P undergoes a course change to correct P. The distance steps at which these events occur, and the segments can be made arbitrarily small, and the results obtained approach the "correct answer" as the steps and segments become small.

This approach results in an accurate representation of the dynamics of the run and observe process, subject only to the validity of the σ_p map and the other inputs to the program. A typical solution would illustrate a transient region where mariners are adjusting to the effects of a resultant wind and current on their vessel, and a steady-state region where the results of this adjustment process have dampened out. The following can be addressed using this model:

- The effect of alternative A/N systems on the duration and amplitude of the adjustment process (the transient), and on the resultant steady state.

- The channel entrance problem; an examination of the transient region for specified wind/current conditions, with specified A/N.

This model is not complete at the present time. The prinicipal area in which the model is incomplete is that simulated real ship movements are not presently included. Rather, when course corrections are required because the information from the A/N has indicated that the ship is not on the desired course, an arbitrary course correction is applied to bring the ship back closer to the desired track. In Phase II, it is planned to replace these arbitrary course corrections with actual ship tracks generated through the Ship Maneuver Model. This was not undertaken during this phase simply because of lack of time—no difficulties are anticipated in accomplishing this refinement.

Preliminary results from the present version of the model are displayed in Exhibits 1 through 16 in the Results section at the end of this Appendix. The curves show the upper and lower 1 percent and 10 percent probability contours for cross-track position (P) and direction of motion (θ) as a function on on-track position (D). The interpretation of the curves is that 98 percent of ships intending to steer the ideal track (displayed on each curve), using the information from the A/N, would actually have cross-track positions within the 1 percent contours of the P versus D curves; and would have directions of motion within the 1 percent contours of the θ versus D curves. A similar interpretation holds for the 10 percent curves. Table B-5 of the Results section defines the cases displayed in these exhibits. Figures B-20 through B-26 were the σ_p maps used for the runs.

The transient and steady-state portions of these figures are readily seen. It appears that in most of the cases the transient portion dies out after about one to three nautical miles.

6.0 Channel Bends

This section presents considerations for the Channel Bend model, and a description of the model.

6.1 Initial Considerations for Channel Bends

A navigator approaching a bend will have predetermined the rudder angle to be used based upon his estimate of how the vessel will respond under the ambient wind and current conditions and the geometry of the bend. He will execute the maneuver when the vessel reaches the appropriate position for the preselected rudder angle. The simplest maneuver would be that which resulted in a track that would put the vessel on a course parallel to the axis of the new channel, with the desired cross-track position, using only the initial rudder command to start and "amidships" to stop the swing. Such a perfect maneuver would require precise knowledge of all variables. There is, however, considerable tolerance in the variables so that the maneuver can be successful (i.e., negotiating the bend safely), even if not perfectly.

The tolerance available for a single rudder angle maneuver may be used to evaluate the effectiveness of the A/N in providing the navigator with the information required to select the point for starting the turn. This is a conservative measure, since the tolerance may be exceeded without hazard if the rudder angle is modified during the turn.

Figure B-27 illustrates the tolerances for a vessel approaching a bend on the channel axis. The tolerance in along-track position is nearly constant for any rudder angle. If the tolerance is exceeded, the maneuver will be initiated in region A or B, requiring that the rudder angle be increased or decreased, respectively, during the turn.

Any error in the estimate of cross-track position will reduce the tolerance. The dotted lines on Figure B-27 show the limits for a vessel with a cross-track position 250' from the axis toward the inside of the turn. The tolerances do not vary significantly (e.g.,

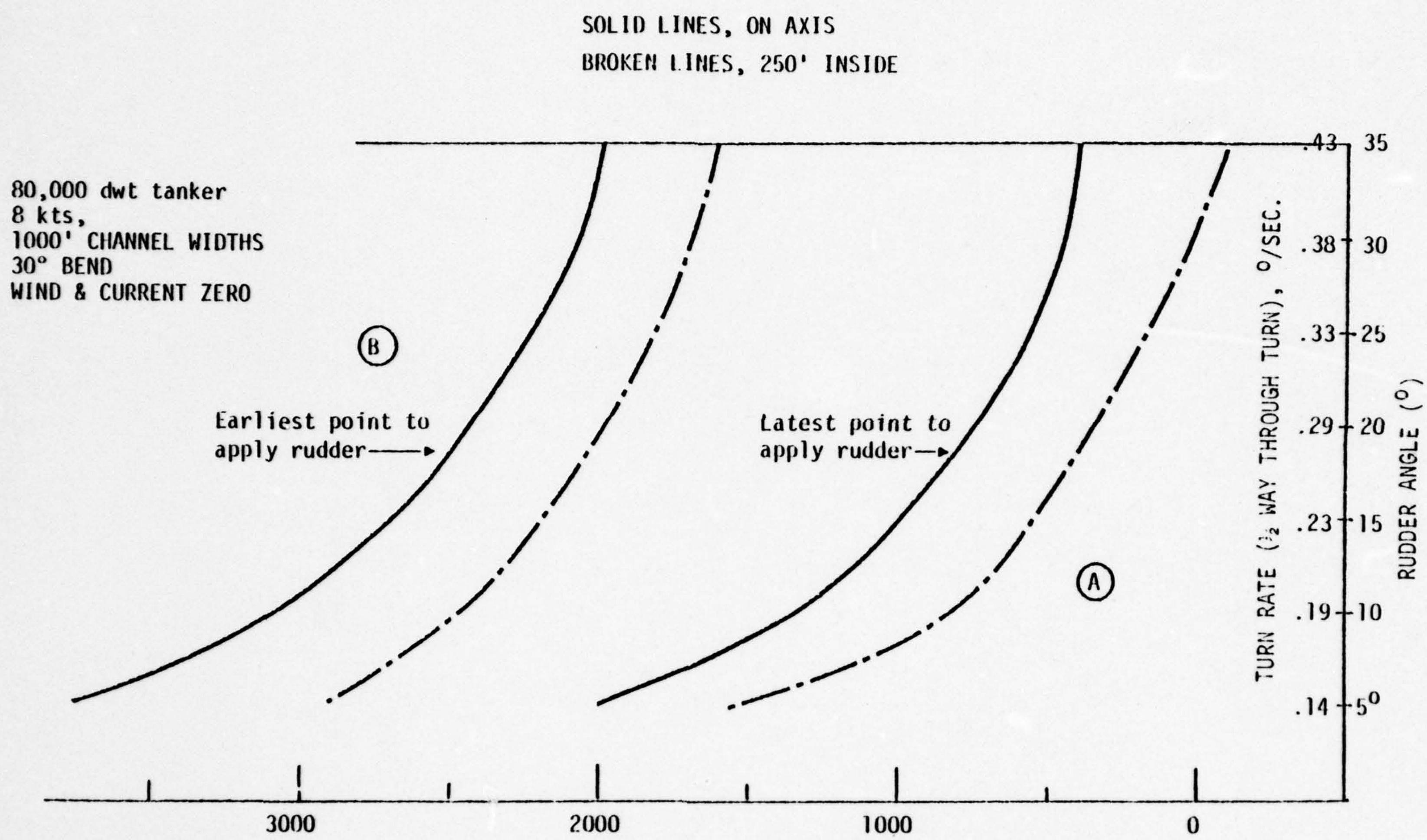

FIGURE B-27. ALONG TRACK POSITION LIMITS FOR A SINGLE RUDDER ANGLE MANEUVER.

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10^{o} to 20^{o}) for rudder angles as a function of cross-track position. Figure B-28 shows the variation in tolerance for tracks on-axis, 250' inside and 250' outside.

The limiting curves will also vary as a function of the angular divergence of the vessel's direction of motion from the channel axis at the time the rudder command is given.

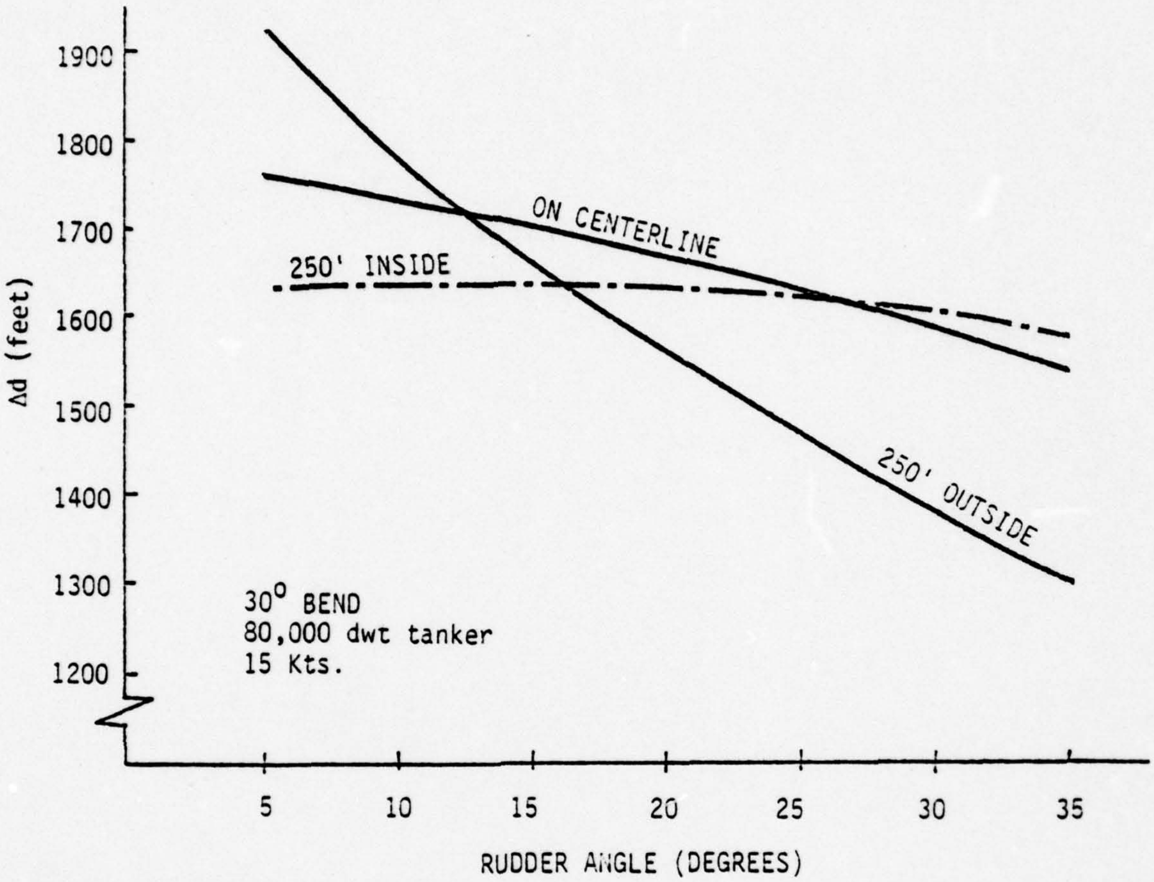
For the bend initiation, the A/N must provide information with respect to cross-track position, direction of motion and along-track position. The first two requirements will be treated in the same manner as for the straight channel case.

Once the turn has been initiated, the navigator monitors the progress of the turn by noting the swing of the bow and his position with respect to nearby A/N. Interviews with pilots indicate that major reliance is placed on the inside turn buoy for position information and that any visible background (even the surface of the water) is used for monitoring the swing of the bow.

The model for the channel bend case will include two distinct modules: an initial point module which treats the errors in cross-track position, along-track position and divergence angle; and a turn monitoring module which treats the observed rate of turn and position determination during the turn.

6.2 Model Description

Identification and quantification of the navigator's response to the observables for the channel bend case have required extensive analysis of the magnitudes and rates of the observables, and careful interpretation of the information obtained through pilot interviews. Pilot interviews have served to point out that in initiating and monitoring a turn maneuver, pilots tend to retain individual styles



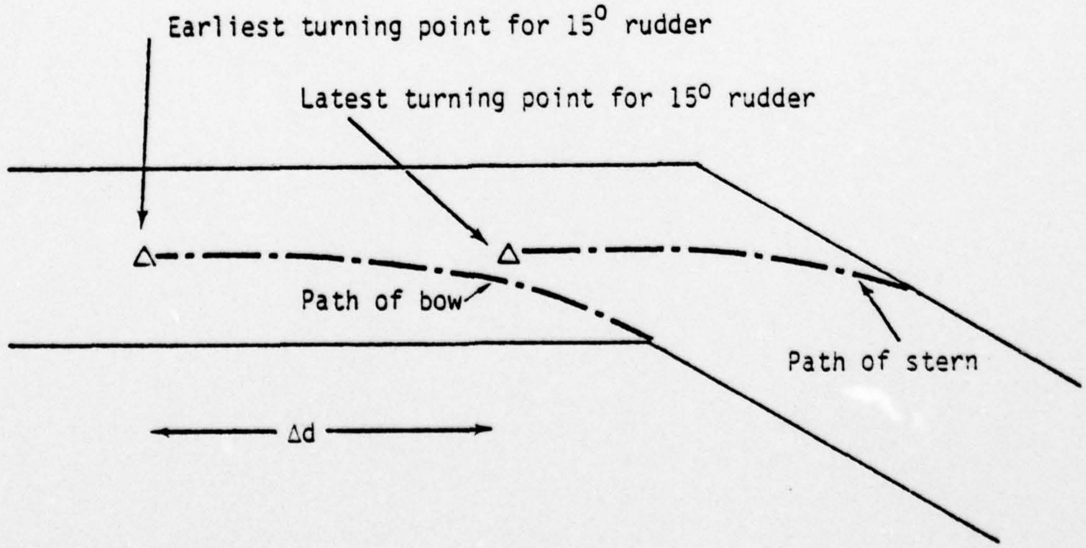


FIGURE B-28. ALONG TRACK TOLERANCES vs CROSS TRACK POSITION.

or techniques. Each has developed an individual sensitivity enabling him to mentally integrate his observations and thus "feel" his rate or turn, direction of motion and safety tolerance. These individual characteristics make human factors modeling in the bend rather complex and efforts are continuing to examine and include all those observables which can be identified and modeled accurately.

The observables included in the channel bend model to date are:

- Visual angle between the inside-turn buoy and the next-ahead buoy on the inside edge (ϕ). This observable is used to initialize turn maneuver decision.
- Bearing to inside-turn buoy (B). This is a turn-monitoring observable whereby decisions to increase or decrease rudder commands are based on expected values of bearing for an ideal path.

The model is described in the following paragraphs and Table B-4 at the end of the description list the significant model elements.

6.2.1 <u>Overview of the Channel Bend Model.</u> Four distinct subtasks have been identified. These are:

a. Ideal path selection.
b. Selection of the initial point (IP). This is the point at which the rudder will be applied.
c. Monitoring the progress of the turn.
d. Aligning the vessel in the new reach.

The observables and navigation parameters for each differ, hence the channel bend model includes a different module for each. Also, the evaluation of each module is dependent on the results from the previous module. The starting point of the channel bend model is a distribution of P and θ derived from the Run and Fix model. These distributions represent the uncertainties in two of the three navigational parameters of

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primary importance in the first module of the turn model. The exit point for the channel bend model is a new set of distributions of P and θ within the "new" reach. The new straight channel reach would then be initialized using this distribution.

6.2.2 Ideal Path Selection. Input to the computer program is the initial rudder command and a time for midships command for what will be considered to be the desired or reference path around turn. From this information, a desired turn initiation point is computed and reference values for the two observables are computed. For the pilot who thinks he is on the ideal path, these reference values will be decision cues in the two computing modules: Initial Point and Turn Monitor. Figure B-29 illustrates a desired path for a 30° bend and the reference observables ϕ_{REF} and B_{REF}.

6.2.3 Initial Point Module. The Initial Point Module receives as input the P-θ distribution from the run and observe model. This distribution represents the density of ships having the navigational parameters, cross-track position (P) and direction of motion (θ). The value of the density in a P-θ segment indicates the proportion of ships which "think" they are on the desired path approaching the bend, but may in fact have an error in one or both navigation parameters. The function of the Initial Point Module is to select a range of possible turn initialization locations for each P-θ density segment.

The decision to initiate a turn is based on the pilot's ability to observe (ϕ) the reference visual angle between the inside-turn buoy and the next-ahead buoy. For each value of P in the P-θ distribution, there is a corresponding value of initial point (IP) for which the reference value of ϕ is observed. The error in a pilot's ability to judge the visual angle is modeled statistically by a normal distribution about the mean value ϕ with a standard deviation σ_{ϕ} = .1ϕ, a

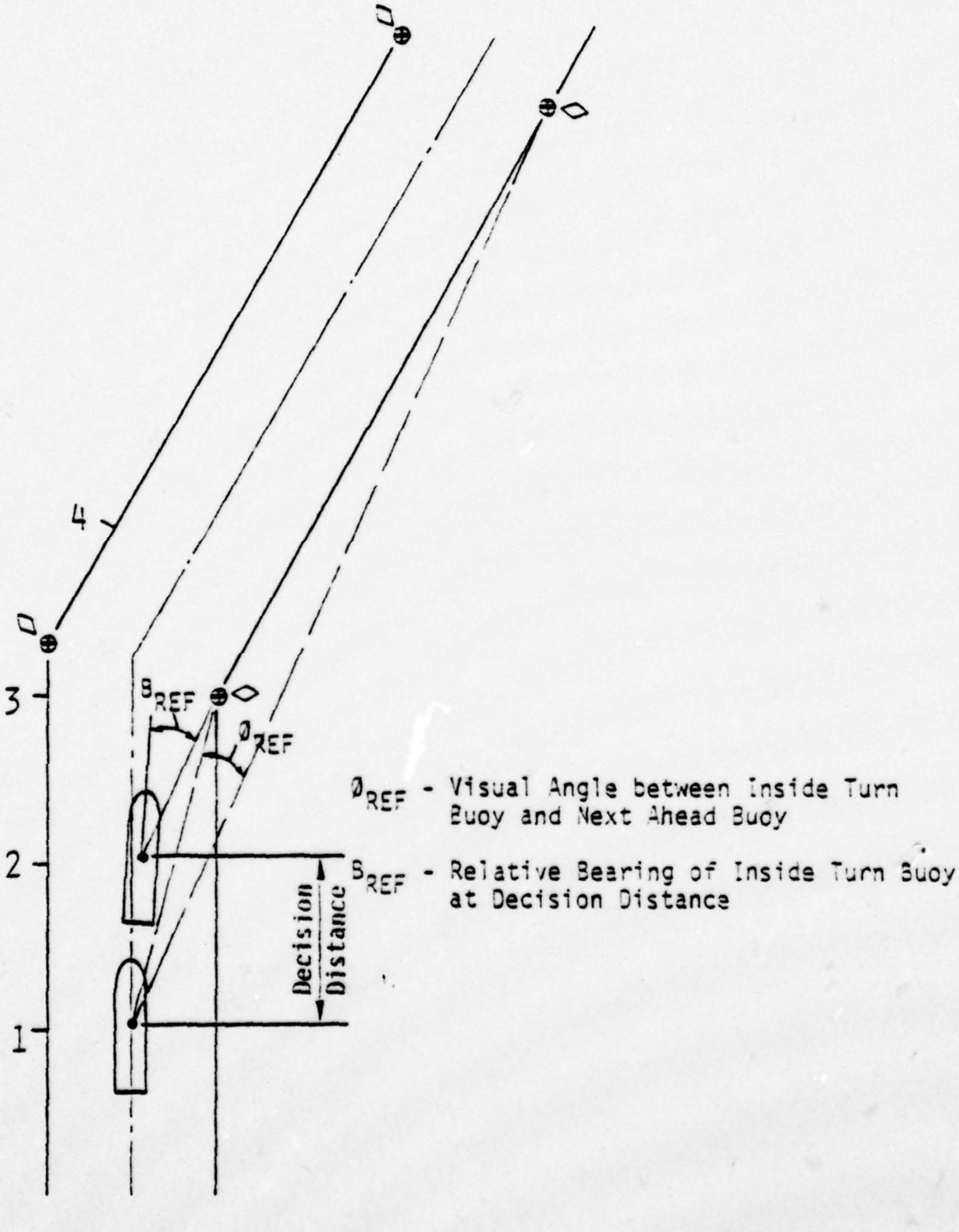

Figure B-29. Reference Observables Are Computed by Ideal Path Module

value which is supported by experiment. Assuming that all pilots can judge this angle within $\pm 4\sigma$, the error in $\emptyset$ can be propagated into a range of initial points about IP and the proportion of values falling within each of the eight 1σ intervals is computed. Figure B-30 illustrates the range of initial points computed for several cross-track locations for a 30° bend.

The output from the Initial Point Module is a 3-dimensional array of P-θ— IP density values.

6.2.4. Turn Monitoring Module. The navigation parameters of primary importance are cross-track position in the old reach, cross-track position in the new reach, direction of motion, and rate of change of direction of motion. The observables are the heading and rate of change of heading, the distances and relative bearing of the inside-turn buoy, and the visual angle between the inside-turn buoy and the buoy next ahead on the inside edge of the new reach.

In the early part of the turn, the most sensitive indication of progress is the relative bearing of the inside-turn buoy. The forward motion of the vessel will tend to make the bearing draw aft, while the rotation of the vessel toward the new reach axis will tend to make it draw forward. For moderately sharp bends (say, 35° to 50°), the relative bearing will remain nearly constant for an appreciable period if the vessel is following a track that will put it on the axis of the new reach. If the bearing draws aft, it indicates that the vessel will pass to the outside of the new reach axis; if it draws forward the vessel will pass to the inside of the new reach axis. This observable provides information on the cross-track position in the "old" reach and the projected track of the vessel. Based on the mariner's ability to identify ship movements which are inconsistent with those expected, a sequence of rudder commands will be initiated to correct the motion to the ideal track.

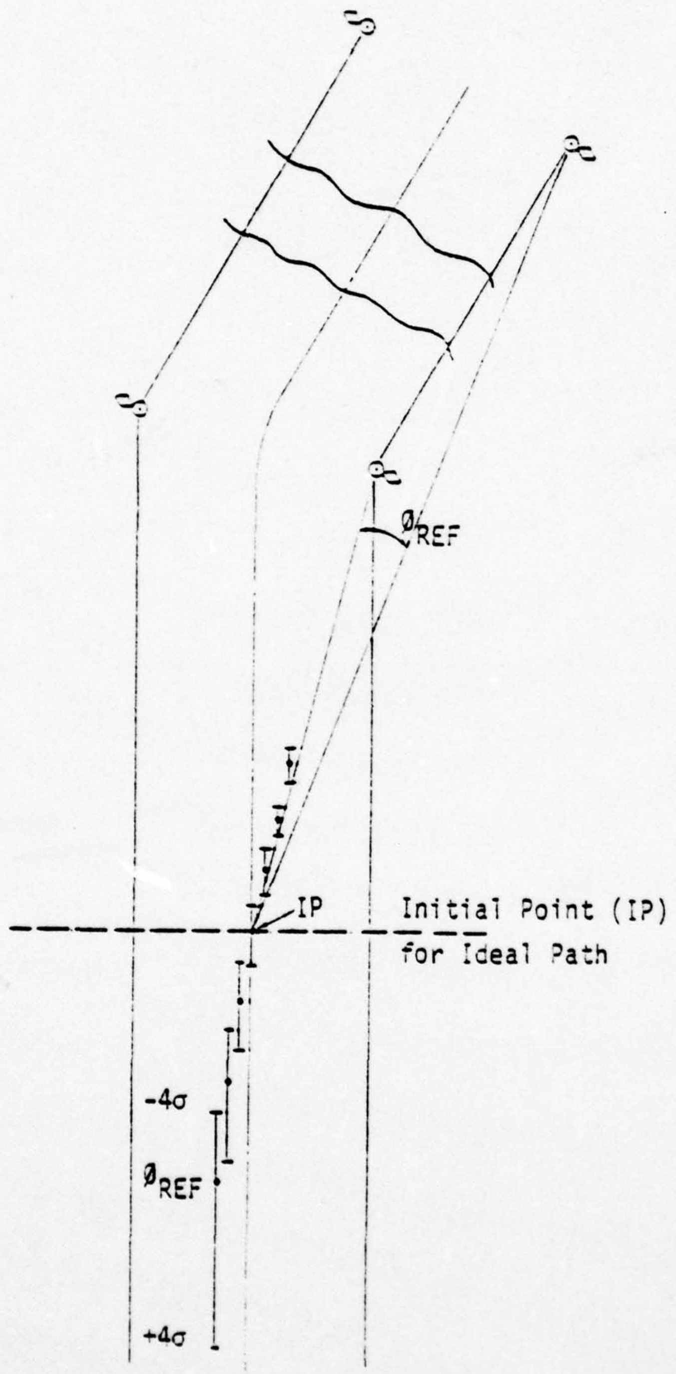

Figure B-30. Initial Point Selection Based on the Observable, ϕ_{REF}, Will Change With Cross-Track Position

As the vessel approaches the extension of the inside edge of the new reach, the visual angles between the buoys will close rapidly. When they are in range, the navigator has a precise indication of his cross-track position in the new channel, and the relative bearing of the buoys will indicate the angle remaining to complete the turn. At this point, the observables change to the aids available in the new reach and the navigation parameters of primary concern become cross-track position and direction of motion.

The function of the Turn Monitor Module is to increase, decrease, or maintain the rudder angle in the turn based on the departure from the expected value of the observable, bearing to the inside-turn buoy (β). The program currently provides for one decision point along the path at a distance which is specified by input. The module makes corrections to the path by the following sequence of computations for each P-θ- IP segment received from the Initial Point Module.

1. Observable β is computed at the decision point.
2. Reference observable β_{REF} having been computed in the Ideal Track Module is compared to β and departure calculated.
3. Adjustments to rudder angle (δ) are selected. These adjustments are shown in Table B-3.

TABLE B-3. RUDDER ADJUSTMENT SCHEDULE FOR TURN MONITORING

Departure from β_{REF}	Correction to Rudder Angle (δ)
-3 to +3^{o}	no correction
Above 3^{o} to 6^{o}	+5^{o} rudder
Above 6^{o}	+10^{o} rudder
Less than -3^{o} to -6^{o}	-5^{o} rudder
Less than -6^{o}	-10^{o} rudder

4. The unmodified P-θ— IP density distribution and path number selection for each P-θ— IP segment is transferred to Alignment Module.

Figure B-31 shows an example of ship maneuvering in a bend with corrected and uncorrected paths. The shaded vessels follow an uncorrected path, whereas the unshaded follow the corrected path that the Turn Monitor Module would select based on the departure of the observable (B) from the expected value B_{REF}. The vessel outlined by dashed lines at the decision point is located at reference position on the desired path where B_{REF} is computed.

6.2.5. Channel Alignment Module. The final module in the computer code produces the resulting P-θ density distribution for the bend maneuver. The procedure is to move each P-θ— IP segment of ships received from the previous computing module into the new reach according to the assigned path number. Cross-track position (P) and direction of motion (θ) as well as the corresponding P-θ segment are computed. The density of ships falling into the segment category is added into the segment value.

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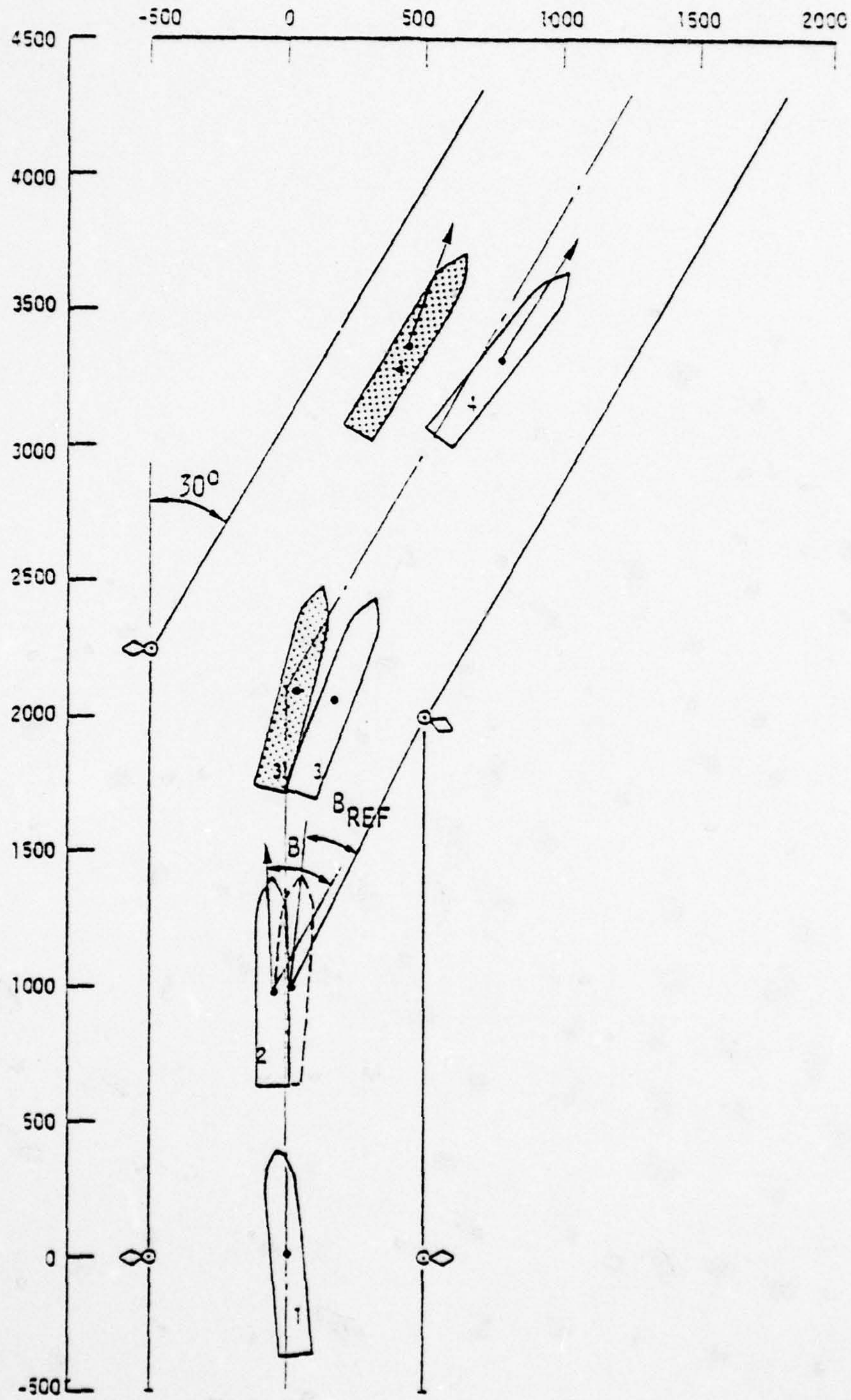

Figure B-31. Ship Monitor Module Corrects Path for Departure in Value of Observable, B, from Expected Value, B_{REF}

TABLE B-4. CHANNEL BEND MODEL SUMMARY

BASIC INPUTS:	P-θ density distribution from Run and Observe Model Bend geometry Aid-to-navigation configuration Vessel selection
<u>IDEAL PATH MODULE</u>	
INPUT:	Initial rudder command, time for mod-ships command and turn monitoring decision distance
FUNCTIONS:	Computes initial point for starting turn for ideal path (IP_{REF}) Computes reference observable values ϕ_{REF} - Visual angle between inside-turn buoy and next ahead buoy at IP_{REF} B_{REF} - Bearing to inside turn buoy at decision distance
<u>TURN MONITOR MODULE</u>	
INPUT:	B_{REF} from Ideal Path module and P-θ-IP density distribution
FUNCTIONS:	The turn monitoring observable (bearing of the inside turn buoy) is computed at the decision distance for each P-θ-IP segment. Departure from the expected value (B_{REF}) is computed. Departures within certain range of values will cause modification to the ideal path to occur (i.e., rudder command may be increased or decreased). New path number is identified from file.
OUTPUT:	P-θ-IP distribution and path number.
<u>ALIGNMENT MODULE</u>	
INPUT:	P-θ-IP distributions and path number of each P-θ-IP segment.
FUNCTION:	Computes new P-θ density distribution at entrance to new channel leg.
OUTPUT:	P-θ density distribution.

II. SAFE/GROUNDING DOMAINS

Summary of Approach

The technique for calculating the safe and grounding domains first establishes the components of motion and location in the vessel's maneuvering plane that can be used to predict grounding of the ship. These key components of motion are called the ship's navigation variables. The combinations of values for these navigation variables that cause the vessel to ground belong to the vessel's grounding domain. The vessel's grounding domain consists of every combination of values for its navigation variables that ensure the vessel will ground. The vessel's safe domain consists of every combination of values for its navigation variables such that grounding could be prevented by an avoidance maneuver.

The navigation variables are selected based upon their influence on grounding of the vessel. The selection of the navigation variables is scenario dependent; the straight channel navigation variables selected were:

1. Direction of motion;
2. Cross-track position, and
3. The magnitude of the vessel's velocity.

The channel bend scenario required one additional navigation variable due to the magnitude of direction change that is required:

4. Angular velocity of the vessel.

The contribution of the vessel's heading to grounding of the vessel should be determined in subsequent refinements to the safe and grounding domain model.

A ship operations model was used to define the grounding domain and safe domain for the vessel. The model utilizes the hydrodynamic equations of motion as described by Dr. Harouzo Eda in a report

on Vessel Maneuvering Simulation (reference 1). The primary grounding domain methodology development was done utilizing the motion associated with an 80,000 DWT tanker in its maneuvering plane. A 250,000 DWT tanker was utilized to illustrate application of the model to a second vessel type.

Straight Channel Safe and Grounding Domains

In a straight channel without additional traffic, it was assumed that the ideal track was to maintain equal distances between the vessel and each side of the channel. Location was expressed as distance from the ideal track, and the direction of motion as the angle between the heading and the ideal track. Cross-track position was the only single condition that could guarantee a grounding. Any ship that was far enough from the center of the channel to touch either side of the channel was considered grounded. When the ship was not touching the bank, some angles of deviation from the ideal track caused grounding. The angle of deviation caused grounding when the ship's turning circle, with maximum rudder angle, intersected the channel side. The conditions for determining that grounding had occurred are outlined in Figure B-32.

Inspection of the conditions for grounding show that different sets of conditions for grounding exist for each type of vessel. For example, the mere size of the vessel alters the distance from the center of the channel for which it grounds, and the maneuverability of the vessel alters the angle of deviation that results in a grounding.

A ship operations model, utilizing maneuver equations based upon hydrodynamic coefficients was used to define the paths of motion for different rudder angles of the vessel. Figure B-33 displays the motions of the 80,000 DWT tanker for different rudder angles at 8 knots. The maximum rudder angle was 35°, and the path defined by the 35° rudder angle was used as the maximum turning capability of the 80,000 DWT tanker. Figure B-33 shows that the tanker needs approximately 2,500 feet to turn its direction of motion through 90° (in still water). The

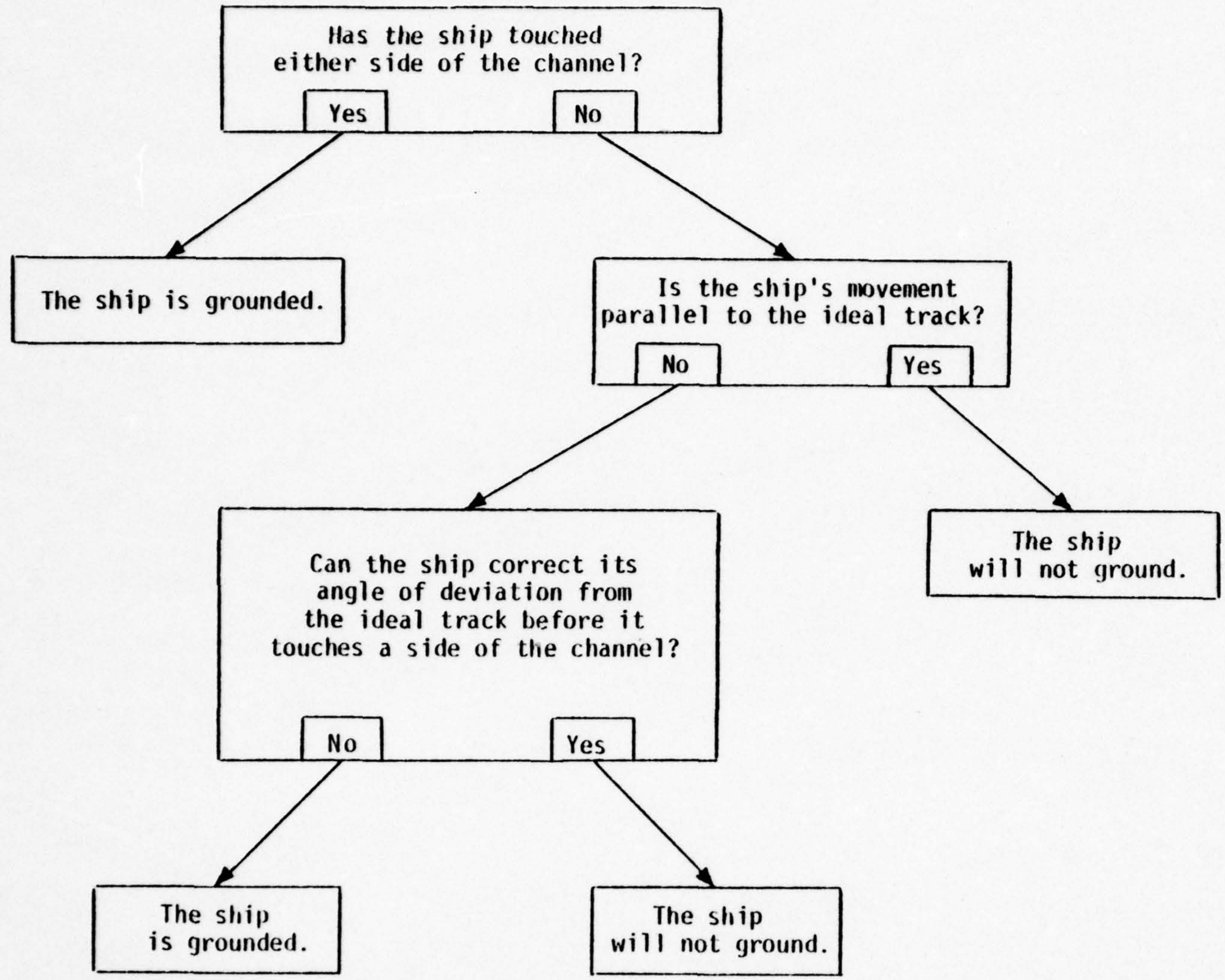

FIGURE B-32. CONDITIONS FOR GROUNDING IN A STRAIGHT CHANNEL

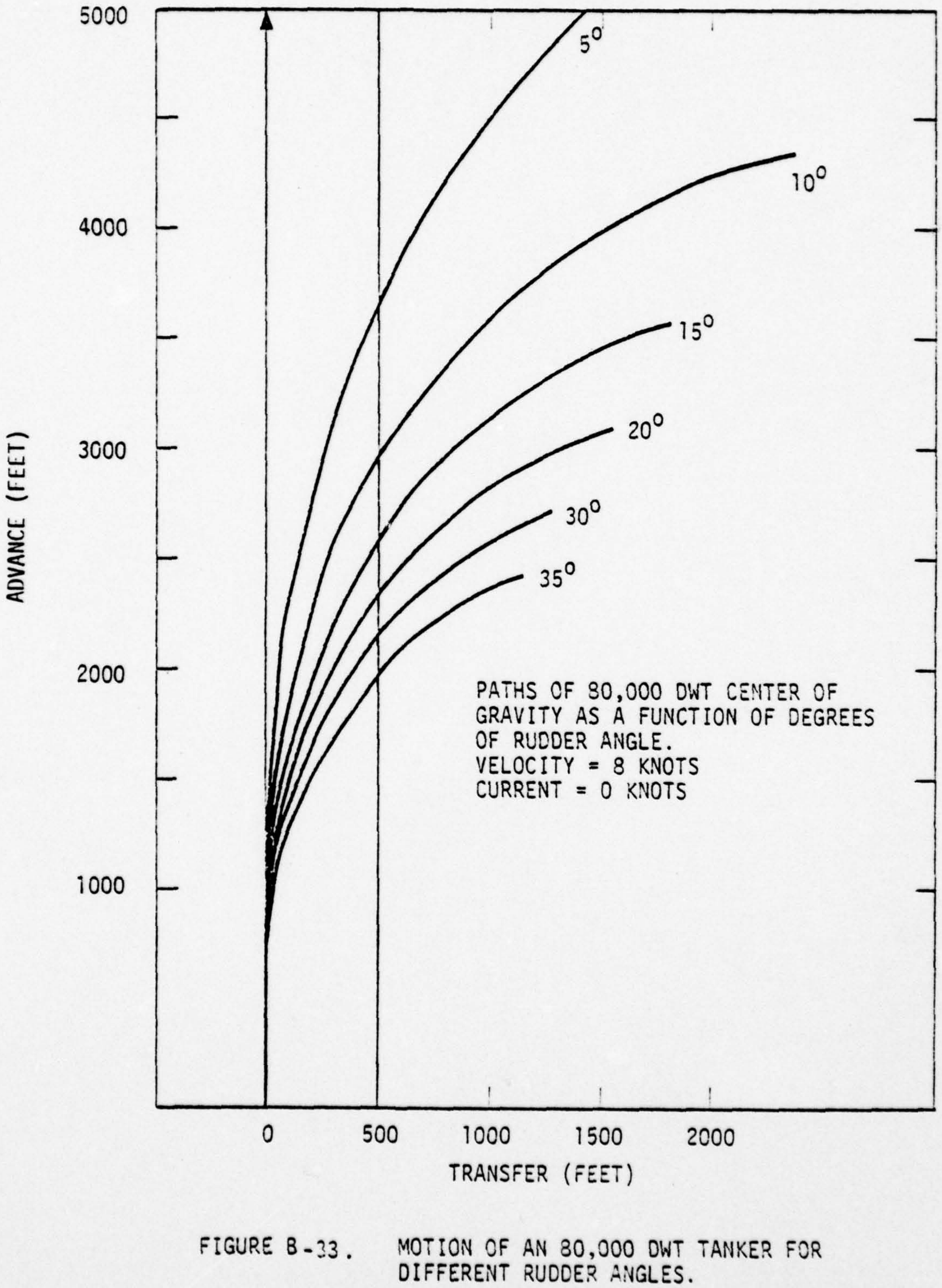

FIGURE B-33. MOTION OF AN 80,000 DWT TANKER FOR DIFFERENT RUDDER ANGLES.

angle of deviation that can be corrected is a function of the maximum turning capability of the vessel and its distance from the side of the channel. The 80,000 DWT tanker shown in Figure B-34 has a distance of 200 feet from the ideal track and a 14^{o} angle of deviation; the maximum turning capability path indicates that grounding will occur. The vessel was considered grounded when it touched a boundary of the channel. The domain of grounding illustrated in Figure B-34 was derived for various distances from the center of the channel.

Ship #1, in Figure B-34, was located 200 feet to the left of the ideal track; any angle of deviation greater than or equal to 14^{o} to the left of the ideal track would guarantee grounding of the vessel. Ship #2 was located on the ideal track; any angle of deviation greater than or equal to 22^{o} to the right or to the left of the ideal track would guarantee grounding of the vessel. Ship #3 was located 100 feet to the right of the ideal track; any angle of deviation greater than or equal to 18^{o} to the right would guarantee grounding of the vessel.

Figure B-35 illustrates all conditions that guarantee grounding for an 80,000 DWT tanker in a 1,000 foot wide straight channel. The calculations for the grounding domains as shown in Figure B-35 did not include current, depth of channel, suction, or cushion which would modify the shape of the grounding domain curve. These factors would be incorporated in subsequent refinements of the grounding domain model.

An analogy can be made between Figure B-34 and Figure B-35. Ship #1 in Figure B-34 illustrated the same grounding conditions as point M in Figure B-35. The conditions of ship #1 and the coordinates of point M each state that grounding of our 80,000 DWT tanker will occur when it is 200 feet to the left of the ideal track and has an angle of deviation to the left of the ideal track greater than or equal to 14^{o}. Point N and point O, respectively in Figure B-35, are equivalent to the conditions of ship #2 and ship #3 in Figure B-34. Point P (800, 18^{o}) serves to illustrate that once a grounding angle has been achieved, any larger angle of deviation would likewise cause a grounding.

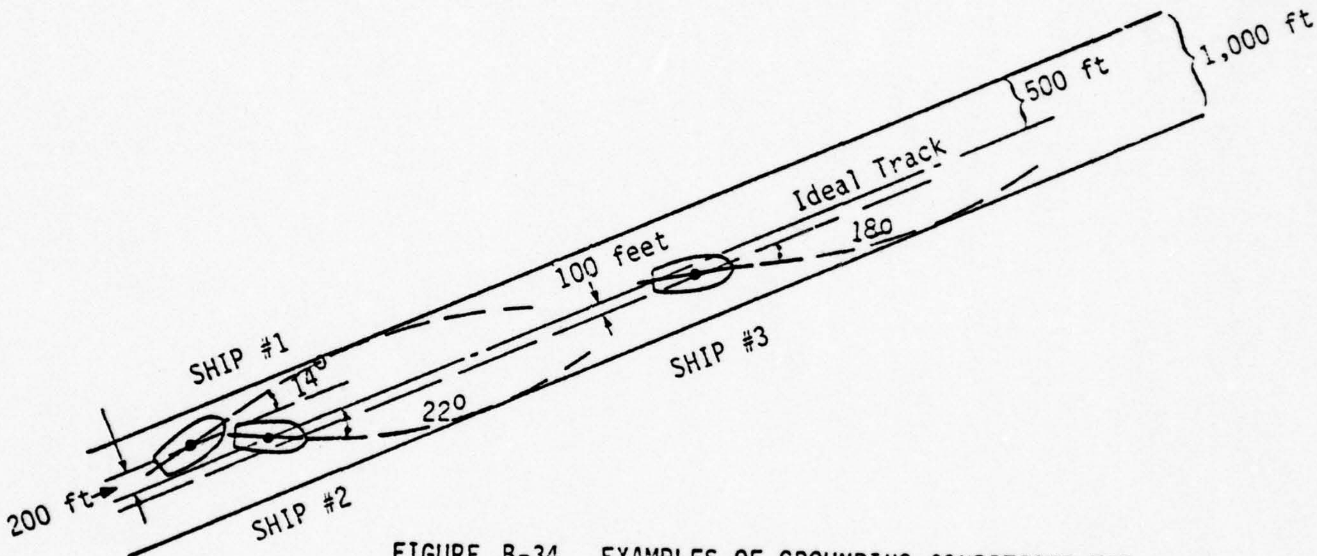

FIGURE B-34. EXAMPLES OF GROUNDING CONDITIONS FOR AN 80,000 DWT TANKER IN A 1000 FOOT-WIDE CHANNEL

Straight Channel Grounding Domain Example

80,000 DWT tanker
8 knots
current/wind = 0

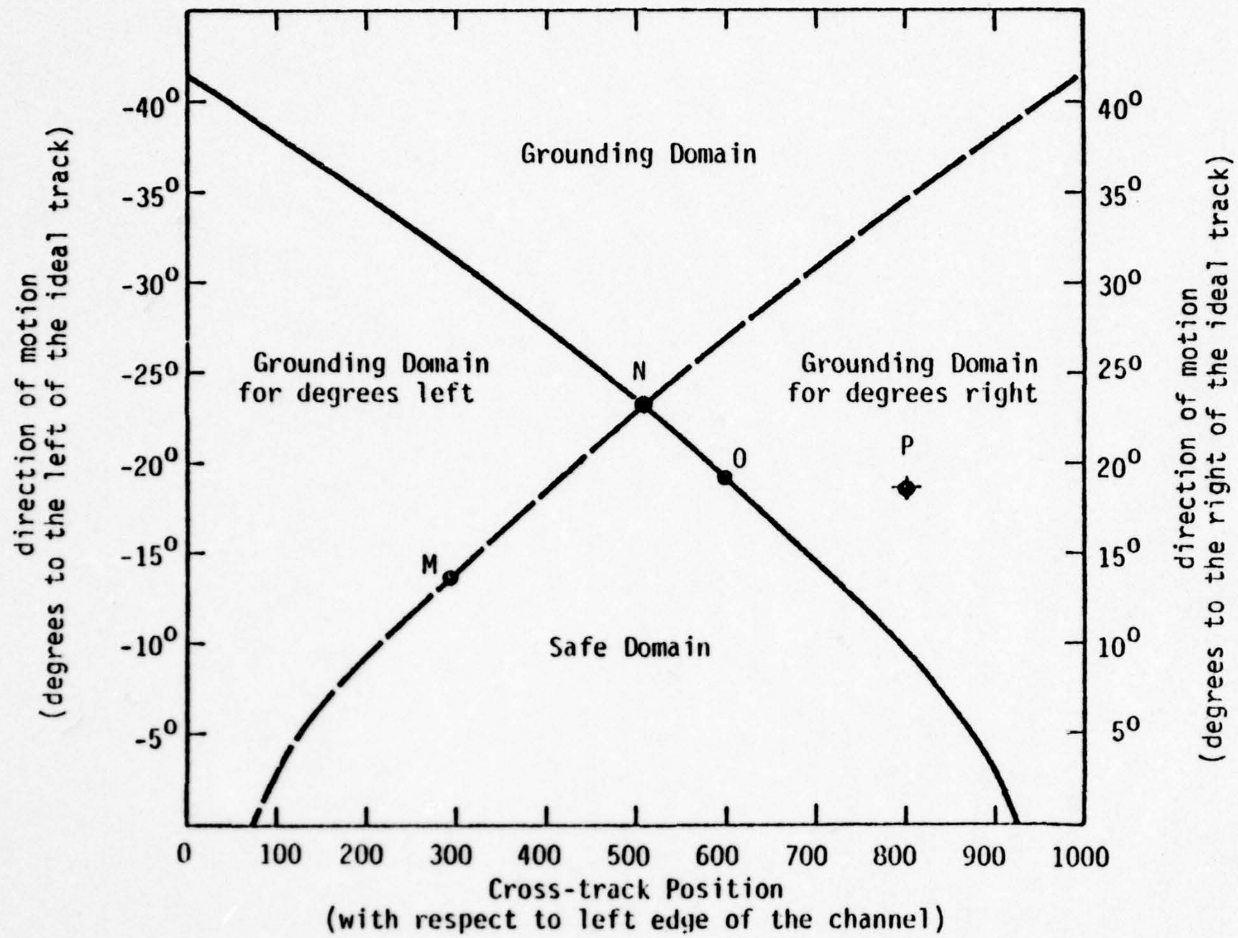

FIGURE B-35. GROUNDING DOMAINS FOR 80,000 DWT TANKER IN A 1000 FOOT-WIDE CHANNEL

Figure B-35 is a graphical representation of the grounding domains that guarantee the grounding of an 80,000 DWT tanker under the assumptions as previously stated. Values of the straight channel navigation variables that correspond to points under the dashed curve will not ground against the left edge of the channel, and values of the navigation variables that correspond to points on the dashed curve or above it indicate that the vessel will ground. Similarly, values for navigation variables that lie below the solid curve indicate that the vessel will not ground against the right edge of the channel, while those points above or on the solid curve indicate that grounding will occur. These results will be used to illustrate a measure of risk in the next section.

A second example vessel was a 250,000 DWT tanker. The motion of the 250,000 DWT tanker is illustrated in Figure B-36. Grounding domain values for a 250,000 DWT tanker traversing a 1000 foot wide channel are shown in Figure B-37. Comparison of the grounding domains associated with an 80,000 DWT tanker (Fig. B-35) and the 250,000 DWT tanker (Fig. B-37) illustrates that the 250,000 DWT tanker requires more distance to correct errors in the vessel's direction of motion. The additional distance needed for correcting the 250,000 DWT direction of motion errors will contribute to increased risk when travelling in confined waterways.

Channel Bend Safe and Grounding Domains

An example calculation for establishing safe and grounding domains for a channel bend is shown in Figure B-38. The example illustrates the elements within the computer model to establish the safe and grounding domains. This computer run initializes the ship maneuvering model with the ship's center of gravity at the origin, heading is set at 57.3°, its speed is 8 knots, and its rudder is preset to 10°. The ship is allowed to progress along its 10° rudder path until its direction of motion is less than 30°. At this time a 35° rudder command is given and

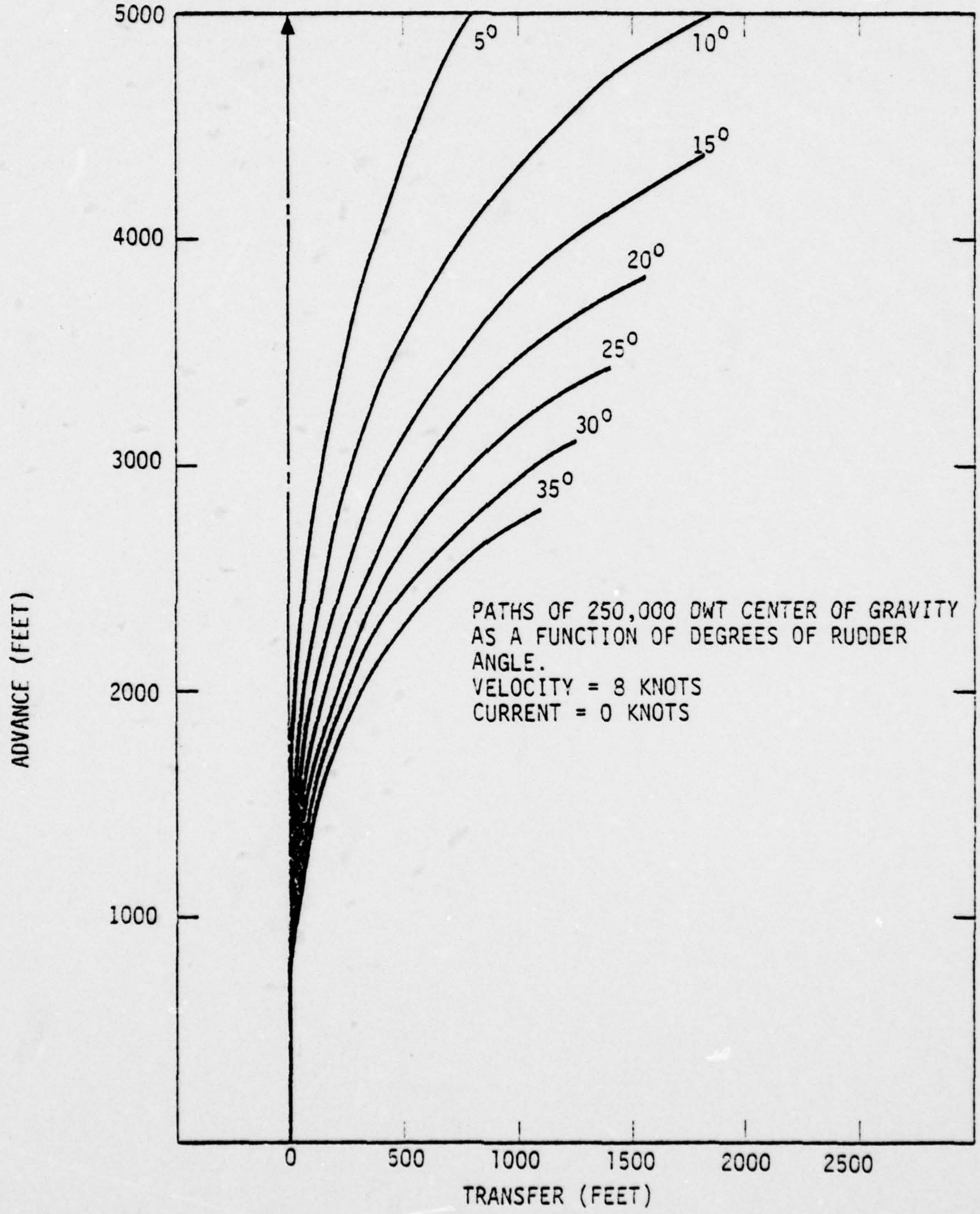

FIGURE B-36. MOTION OF A 250,000 DWT TANKER FOR DIFFERENT RUDDER ANGLES.

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Straight Channel Grounding Domain, Example 2

250,000 DWT Tanker
8 knots
current/wind = 0

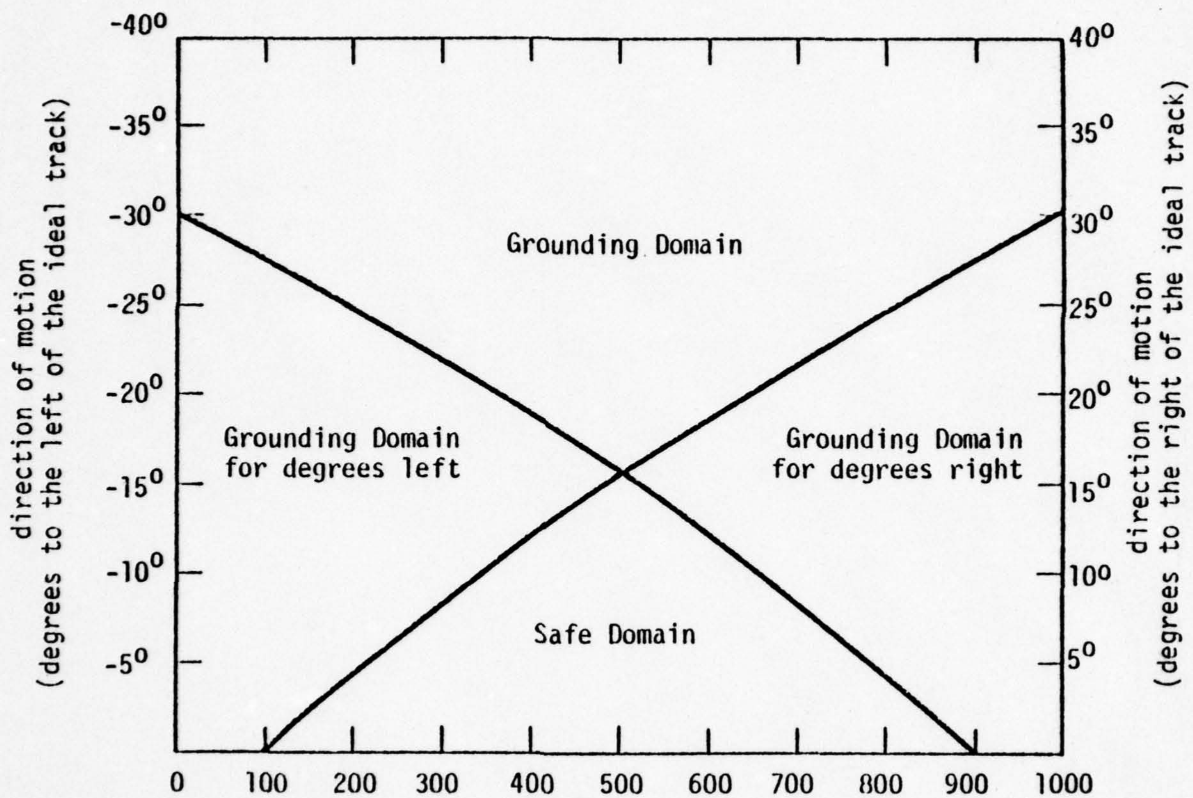

FIGURE B-37. 250,000 DWT TANKER GROUNDING DOMAIN EXAMPLE

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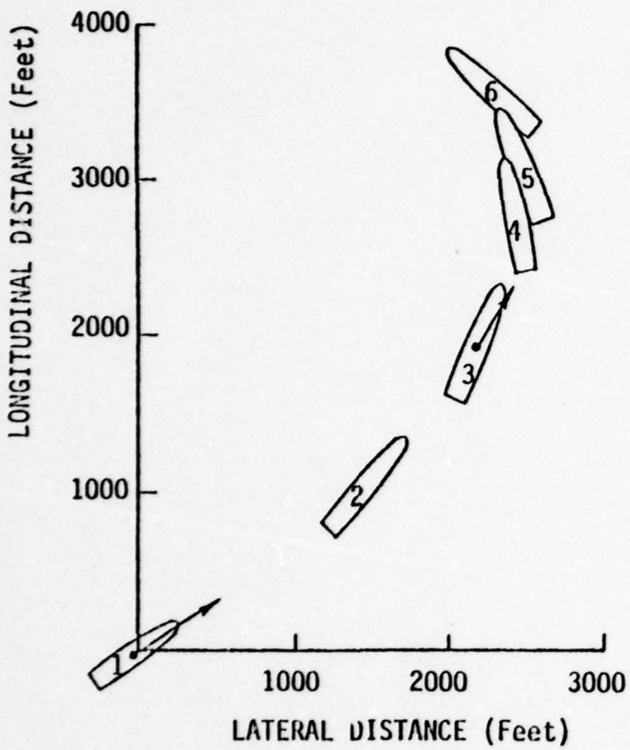
80,000 DWT TANKER
8 KNOTS = INITIAL SPEED
57.3^0 = INITIAL HEADING
57.3^0 = INITIAL DIRECTION OF MOTION
0 = INITIAL ANGULAR VELOCITY



TIME	HEADING	DIRECTION OF MOTION	SPEED	ANGULAR VELOCITY	STERN Y	RUDDER
t_1=.001	57.3^0	57.3^0	13.5ft/sec	0	-321.ft	10^0
t_2= 135	41.8^0	46.8^0	13.2ft/sec	$-.195^0$/sec	1209.ft	10^0
t_3= 225	21.5^0	29.3^0	12.5ft/sec	$-.252^0$/sec	2039.ft	18.6^0
t_4= 300	-9.4^0	- .6	10.4ft/sec	$-.447^0$/sec	2514.ft	35^0
t_5= 330	-22.4^0	- 6.2	9.4ft/sec	$-.406^0$/sec	2596.ft	35^0
t_6= 390	-46.8^0	-27.8	7.8ft/sec	$-.384^0$/sec	2593.ft	35^0
			Initialize			
t_1= 221 sec		29.9052		$-.243^0$/sec	2161.ft	10^0
			Final			
$t_f \approx$ 363 sec		-		-	2616.ft	35^0

Grounding Domain Values

Direction of Motion = 29.9052^0
Angular Velocity = $-.243^0$/sec
Distance to Grounding Constraint = 455' = 2616-2161

FIGURE B-38. EXAMPLE OF CALCULATION FOR BEND GROUNDING DOMAIN

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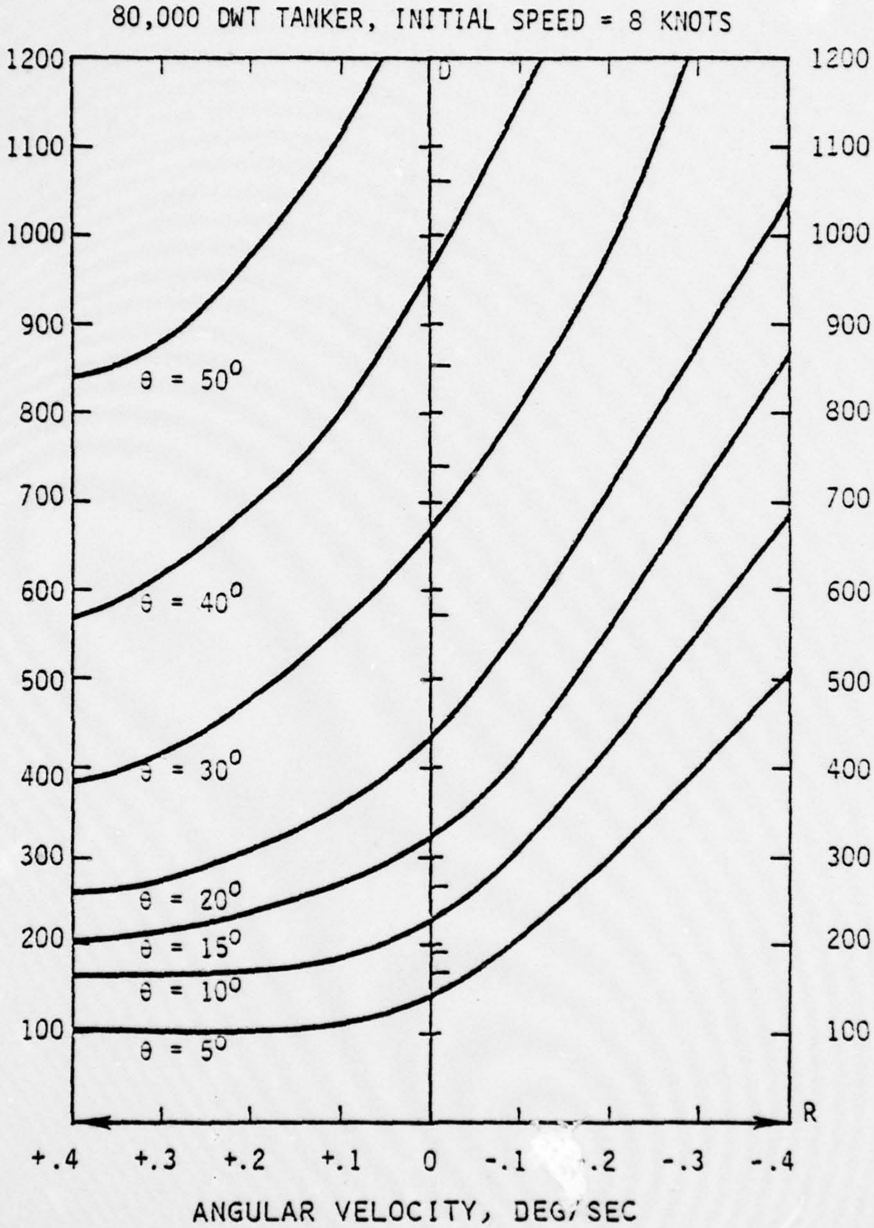
the values of the navigation variables are initialized. This event occurred 221 seconds into the run as shown on Figure B-38. The ship then proceeds through its maximum turning capability and the stern is tracked to determine the maximum lateral distance traveled. The maximum lateral distance is corrected by the lateral distance of its center of gravity at the time the values of the navigation variables were initialized, thus giving the lateral distance needed to complete the avoidance maneuver. This combination of initial direction of motion, initial angular velocity, and calculated lateral distance traveled after the initialization define a point on the vessel's grounding domain when compared to a channel edge or other grounding constraint. The table shown in Figure B-38 illustrates important motion parameters and their values throughout the calculation.

The entire set of grounding domain values for a channel bend can best be illustrated by Figure B-39. The angular velocity and distance combinations that assure grounding for various directions of motion toward a grounding constraint are illustrated. The angular velocity becomes extremely important for large angles; and not as important for small angles of motion toward a grounding constraint. The angular velocity can increase the distance needed to complete an avoidance maneuver by more than 400 feet when the angular velocity is in the opposite direction of a desired turn. Points above a selected θ curve in Figure B-39 indicate that grounding will not occur, while points below the selected θ indicate that grounding will occur.

Angular velocity becomes very important when the direction of motion toward a grounding constraint is large. Directions of motion toward the edge of a channel frequently are greater than 30^{o} when the vessel is negotiating a channel bend. Directions of motion toward the edge of a channel are seldom very large when negotiating a straight channel. For this reason, angular velocity was not considered as a navigation variable in the straight channel but was of necessity considered as a navigation variable in the channel bend scenario.



θ = DIRECTION OF MOTION OF THE VESSEL (DEGREES)
D = DISTANCE TO THE GROUNDING CONSTRAINT (FEET)
R = ANGULAR VELOCITY OF THE VESSEL (DEGREES/SECOND)

FIGURE B-39. GROUNDING DOMAINS FOR A SINGLE CONSTRAINT

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III. RISK AND TRAFFIC FACILITATION

1.0 Measure of Risk

Risk will be measured by considering the distributions of the values for the navigation variables produced by the aids to navigation, the grounding domain for the particular type of vessel, and the ideal track that the vessel is attempting to follow.

A method for determining risk will be illustrated by showing a calculation of risk associated with the scenario described below:

SCENARIO

- 1000 foot wide straight channel
- Gated buoys (6000 feet apart)
- Infinite Water depth
- Ideal track is center of channel
- Current/wind = 2 knots (perpendicular to ideal track)
- 80,000 DWT tanker
- Speed = 8 knots.

The first step in assessing risk is to determine the density function for the straight channel navigation variables. The bivariate probability density function (PDF) for the ship's direction of motion and cross-track position is an output from the human factors model. Figure B-40 illustrates the PDF for the above scenario at the 1 nautical mile mark after entering the straight channel. From this figure, the frequency of having a direction of motion of 1^{o} to the right while maintaining a cross-track position of 500 feet from the left edge of the channel is approximately 26 out of 1000 trips through the channel (after traveling the first 6000 ft. of the channel) for the scenario being illustrated. The discrete cells with their associated frequency of occurrence are utilized for the example calculation of risk.

The PDF for θ and P as shown in Figure B-40 is dependent upon the ideal track that the vessel is trying to maintain. The distribution would change significantly should the vessel try to maintain a track

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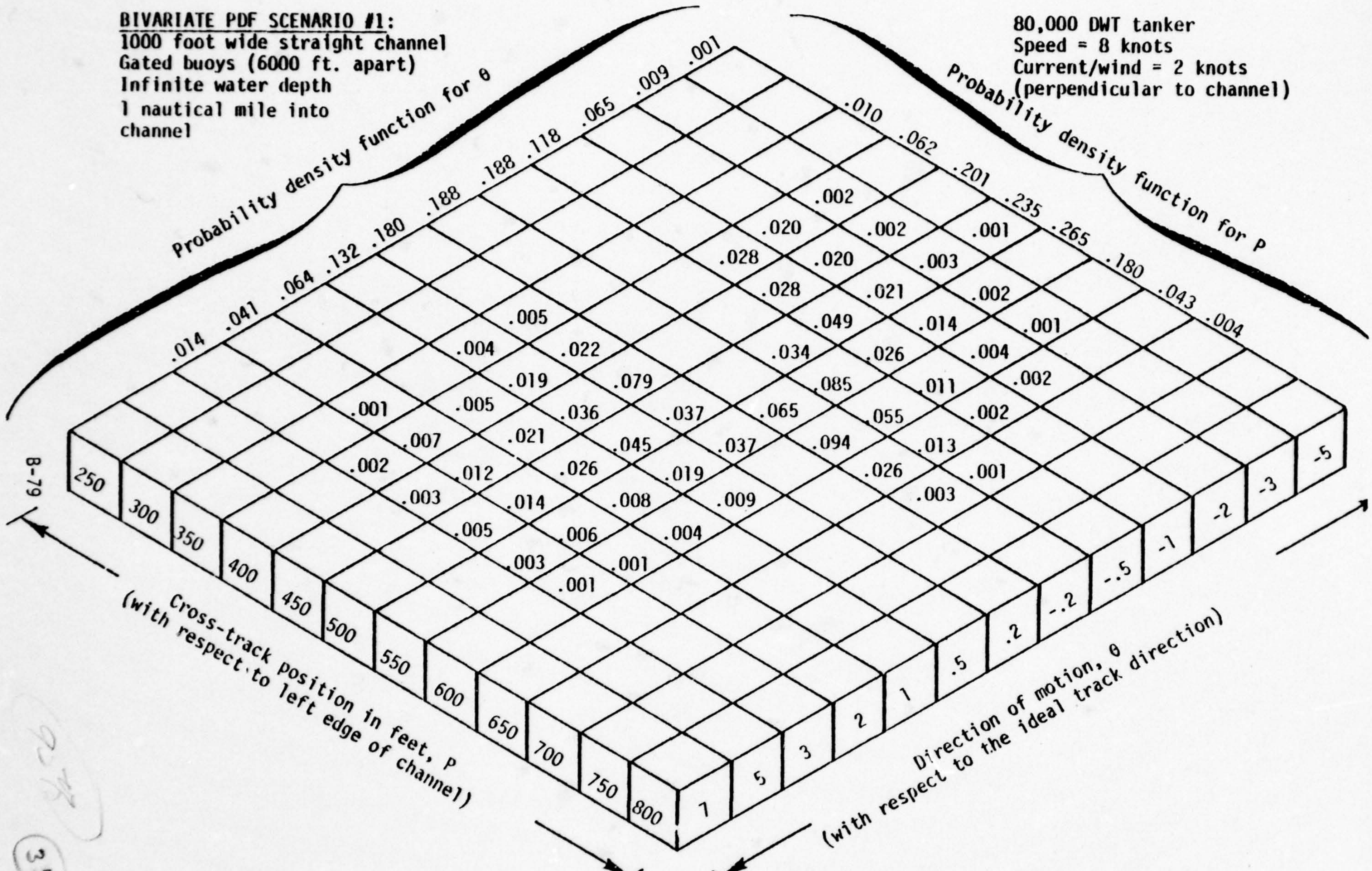

FIGURE B-40. EXAMPLE OF A BIVARIATE DENSITY FUNCTION FOR VALUES OF STRAIGHT CHANNEL NAVIGATION VARIABLES

750 feet from the left edge of the channel. This change is due to uncertainties in crosstrack position being different for each ideal track.

The second step in determining risk is to evaluate the grounding domain of an 80,000 DWT tanker for the above scenario. Figure B-41 illustrates the grounding domain for this scenario, with the exception that current/wind was considered to be zero. The grounding domain values in Figure B-41 will be used to illustrate the calculation of risk methodology.

A preliminary measure of risk will be in terms of time that the aids to navigation system provides to the pilot for decision and execution of course changes due to incorrect directions of motion. In other words how much time must elapse without a course change before the vessel enters its grounding domain.

The third step in determining risk will be to determine the distribution of pilot decision times and the frequencies of occurrence associated with the bivariate probability density function of θ and P shown in Figure B-40. Each cell of the PDF corresponds to a pilot decision time and a frequency of occurrence for that pilot decision time. Figure B-42 illustrates the relationship of the bivariate probability density function of θ and P to the pilot decision time and its respective frequency of occurrence. For each value of θ and P, a single pilot decision time is determined. The frequency of a particular pilot decision time is determined by the sum of the frequencies for the cells in the θ, P PDF that correspond to the particular pilot decision time. Figure B-42 shows two examples of the matching of the θ, P cells to their respective pilot decision times.

The method for calculating the pilot decision time is illustrated for a special case in Figure B-43. The case shown and the equations below only consider a vessel moving to the right. An alternate equation exists when a vessel is moving to the left.

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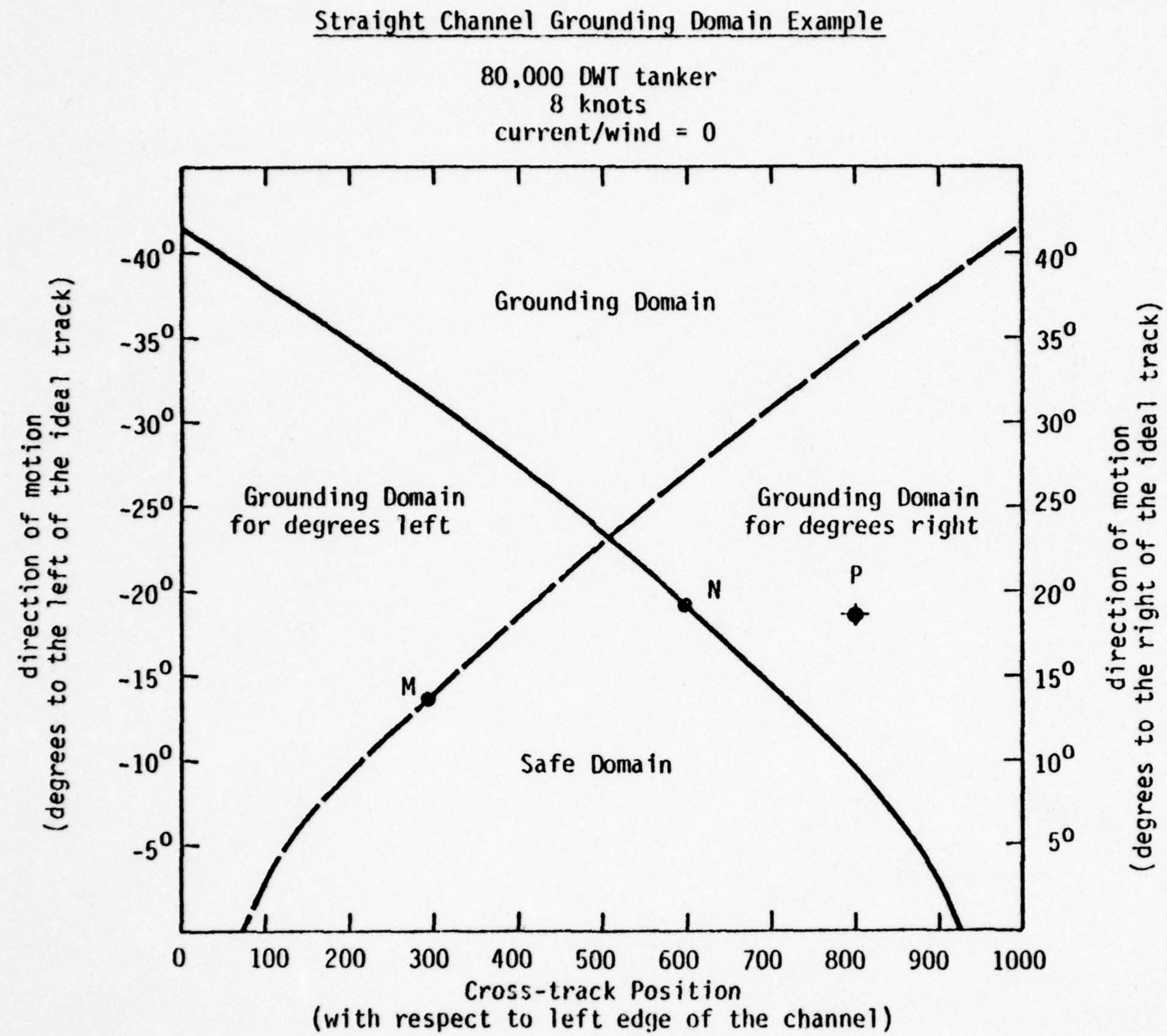

FIGURE B-41. GROUNDING DOMAINS FOR 80,000 DWT TANKER IN A 1000 FOOT-WIDE CHANNEL.

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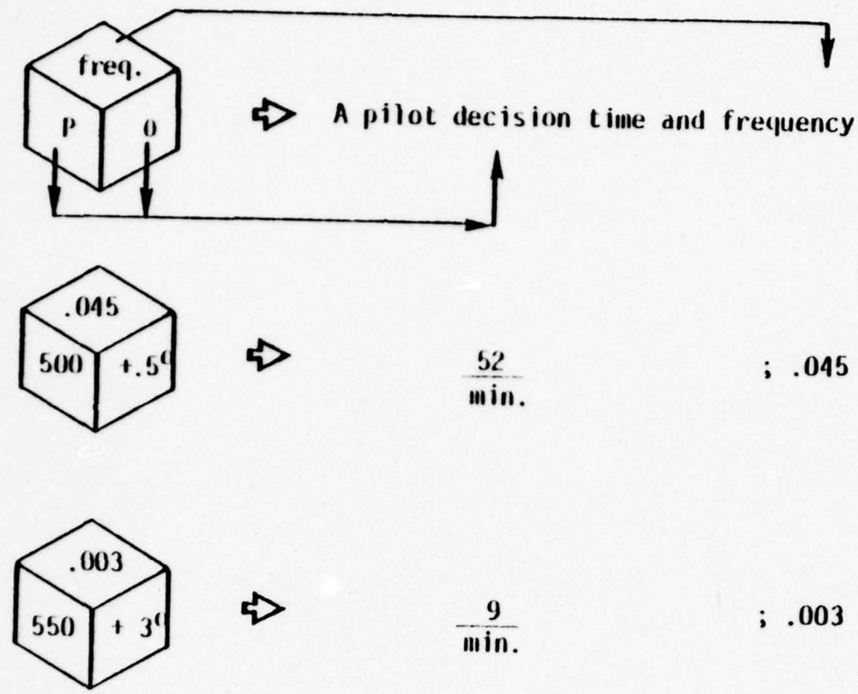
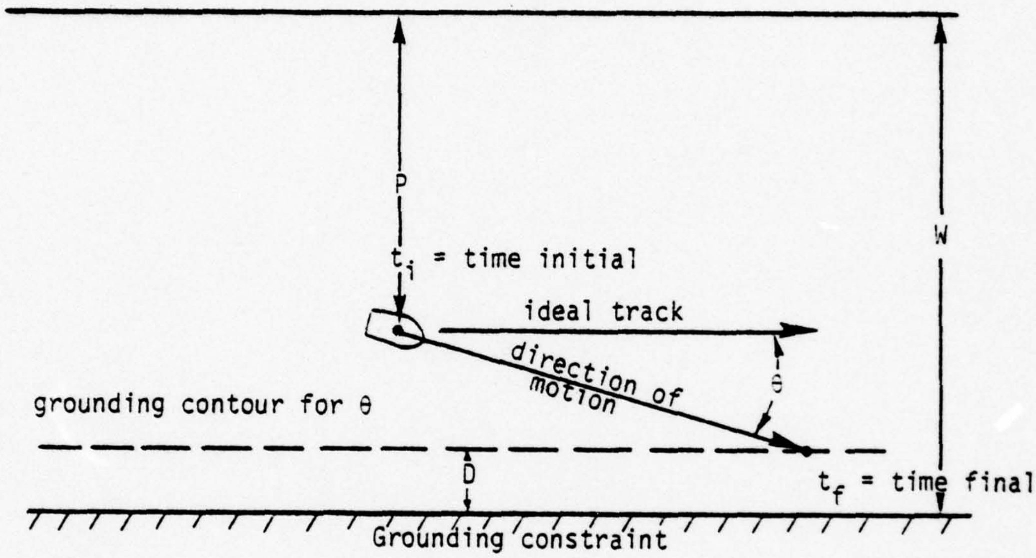


FIGURE B-42. PILOT DECISION TIME EXAMPLES



$t_D = t_f - t_i$; pilot decision time

P	; distance to the left grounding constraint
$\vec{v}$	; vessel speed in direction of motion
D	; grounding domain distance for angle θ
θ	; direction of motion with respect to the ideal track
W	; width of channel.

FIGURE B-43. ILLUSTRATION OF PILOT DECISION TIME VARIABLES

The equation for pilot decision time when the vessel is moving to the right is:

$$\text{Pilot decision time} = \frac{W-P-D}{\sin(\theta)\cdot v\cdot 60 \text{ sec/min}}$$

P is given in feet from the left edge of the channel, D is given in feet from the right edge of the channel, θ is given in degrees, and $\vec{v}$ is given in ft/sec. This results in a pilot decision time that can be rounded to the nearest minute. The equation for pilot decision time when the vessel is moving to the left is:

$$\text{Pilot decision time} = \frac{P-D}{|\sin(\theta)|\cdot\vec{v}\cdot 60 \text{ sec/min}} .$$

A probability density function for pilot decision times was built be integrating pilot decision times and their frequencies of occurrence resulting from consideration of all cells in the θ, P bivariate probability density function shown in Figure B-40. The PDF for pilot decision times developed is shown in Figure B-44. This PDF for pilot decision times results from the best possible information that the pilot can perceive and assumes perfect implementation of course changes that are required. The pilot or crew errors that might occur after the pilot perceives danger are not considered. The results of this modeling produce relatively large pilot decision times and reflect the effectiveness of the aids to navigation system to provide the pilot with necessary information. This measure of pilot decision times will provide a qualitative instrument for comparing different types of aids to navigation such as gated buoys vs. ranges, etc. The PDF for pilot decision times, as shown in Figure B-44, has three characteristics that should be addressed. The first is the region between 0 minutes and 60 minutes. These relatively short decision times are the result of directions of motion greater than 1° from the ideal track. The second region to be considered is above 160 minutes. This is a result of angles of deviation less than 1° from the ideal track direction. The third region

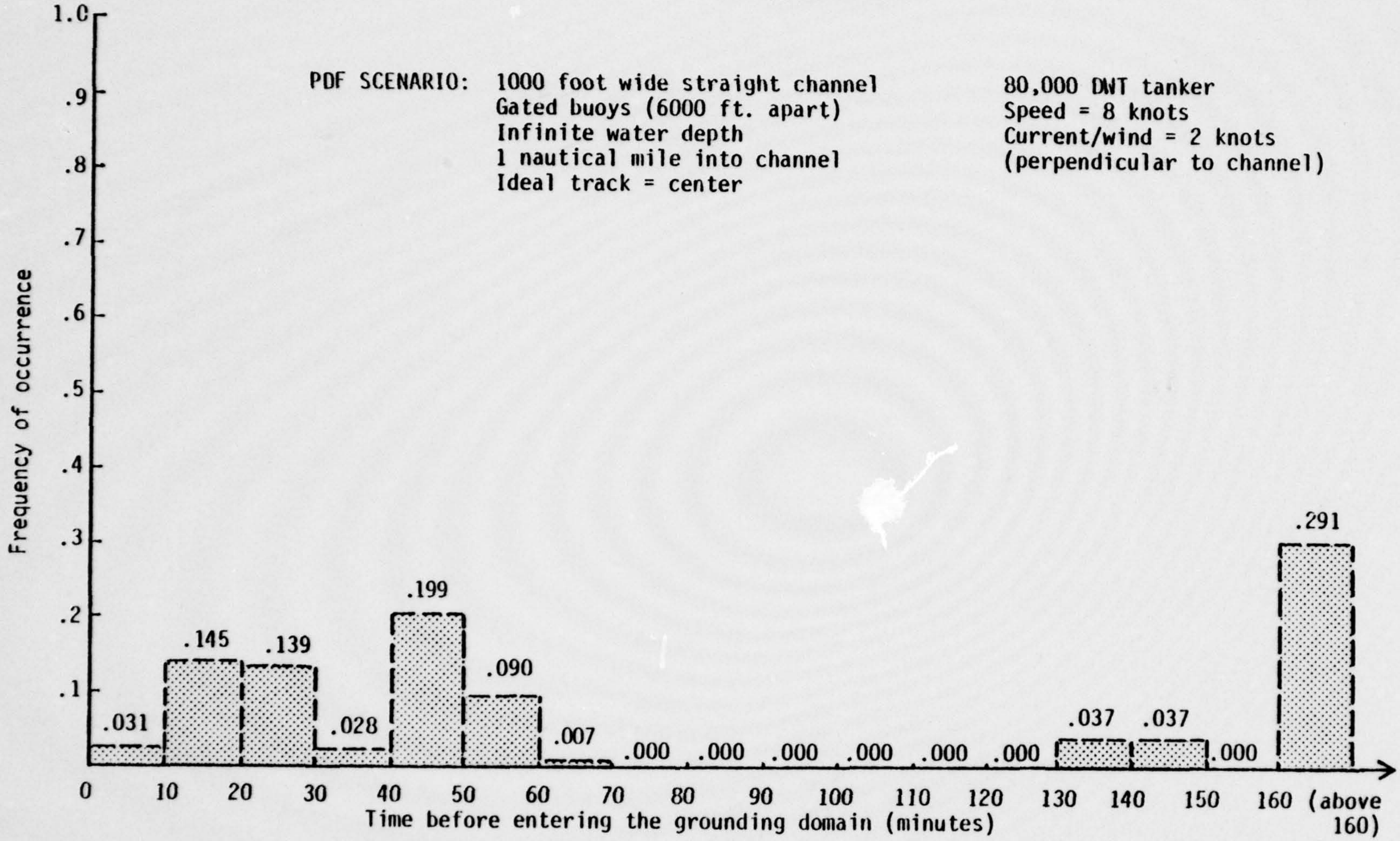


FIGURE B-44. EXAMPLE OF A PROBABILITY DENSITY FUNCTION FOR PILOT DECISION TIME

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of interest is the region between 70 minutes and 130 minutes. This region was the result of insufficient divisions for the directions of motion. The third region was corrected by using smaller increments in the directions of motion when calculating the probability density function shown in Figure B-40.

Vessels traveling near to their grounding domain and their associated frequencies provide significant insights into the effectiveness of an aid to navigation system. Those densities that lie near zero stand the greater risk of grounding.

A cumulative distribution function (CDF) for the PDF of pilot decision times is shown in Figure B-45. The cumulative distribution facilitates obtaining information regarding the frequencies of ships traveling within a selected time limit from the grounding domain. For example, Figure B-45 illustrates that 31.6 percent of the ships traversing the straight channel in our defined scenario are within 30 minutes of grounding at the one nautical mile mark. The cumulative distribution function for the same vessels at 3 nautical miles into the channel is shown in Figure B-46. It shows that after 3 miles into the channel that only 14.3 percent of the ships traversing the channel are within 30 minutes of the grounding domain. Figure B-47 shows that when the vessels have traveled 6 nautical miles into a straight channel marked by gated buoys, less than one percent of the vessels should be within 30 minutes of the grounding domain.

Two properties of the CDF should be considered when comparing alternate systems for aids to navigation:

1. Percentage of the vessels traveling near to the grounding domain.
2. Improvement in the relatively small pilot decision times due to errors in direction of motion upon entering the channel.

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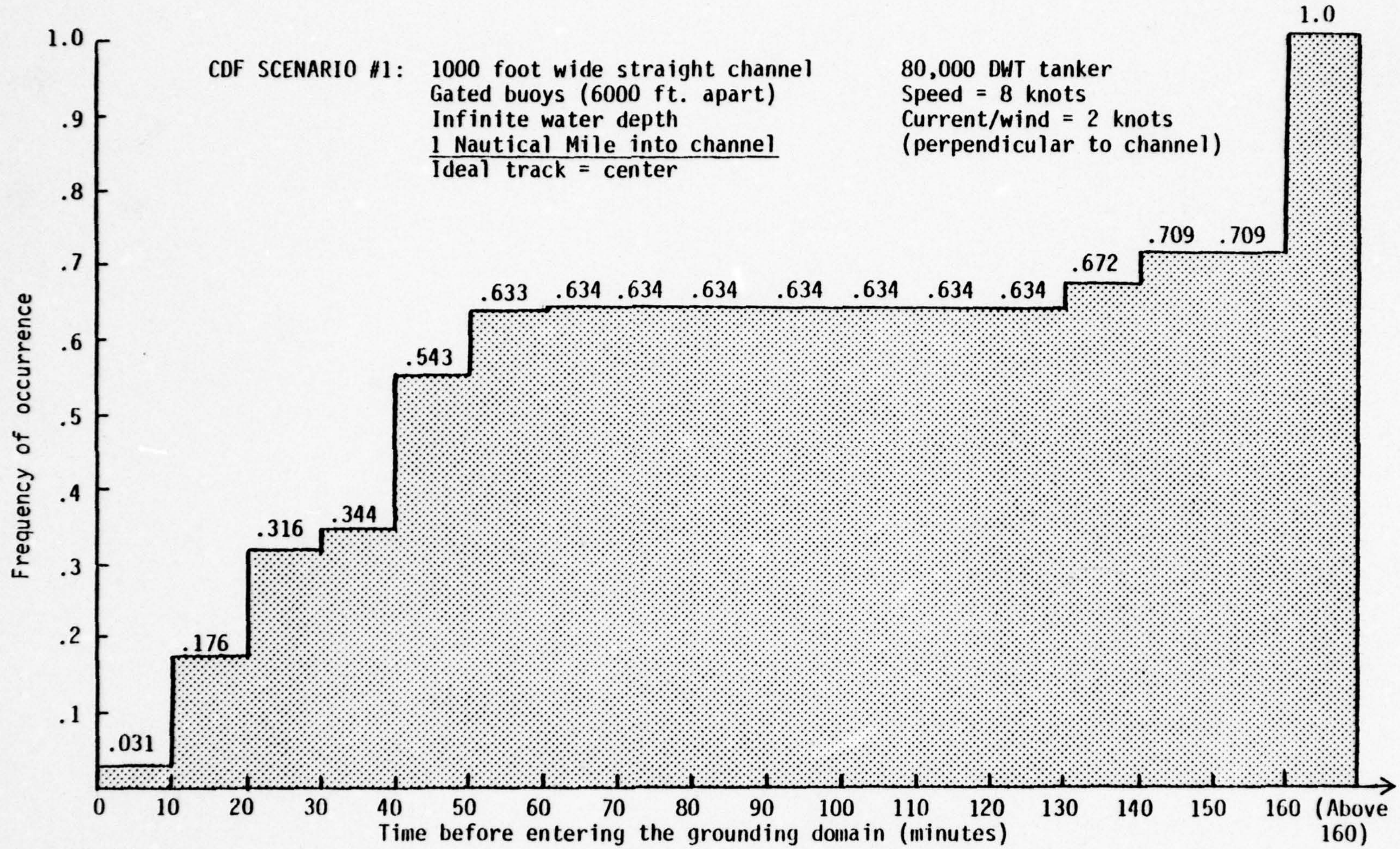

FIGURE B-45. CUMULATIVE PROBABILITY DISTRIBUTION FOR PILOT DECISION TIMES, EXAMPLE #1

95 1/6

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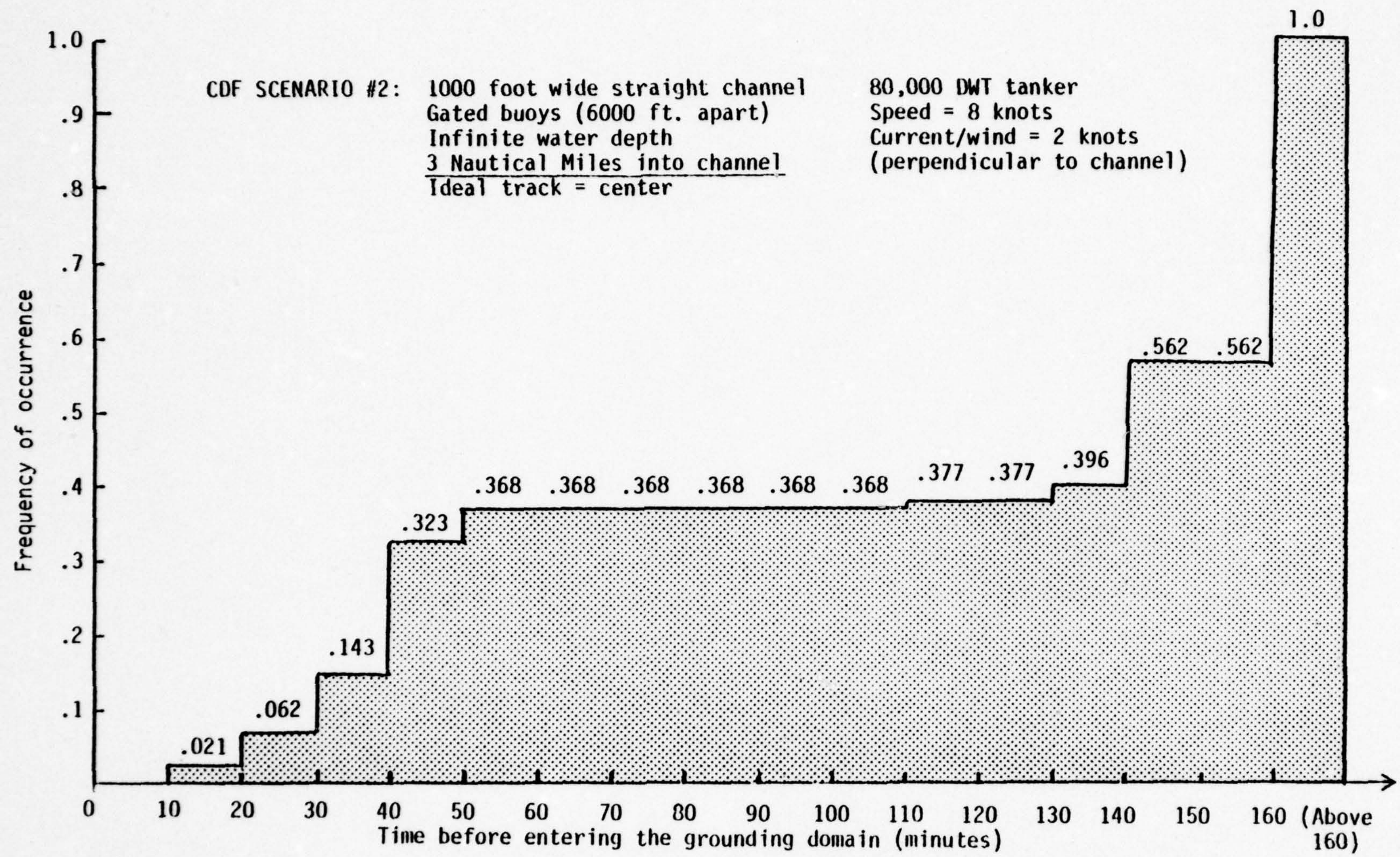

FIGURE B-46 CUMULATIVE PROBABILITY DISTRIBUTION FOR PILOT DECISION TIMES, EXAMPLE #2

360

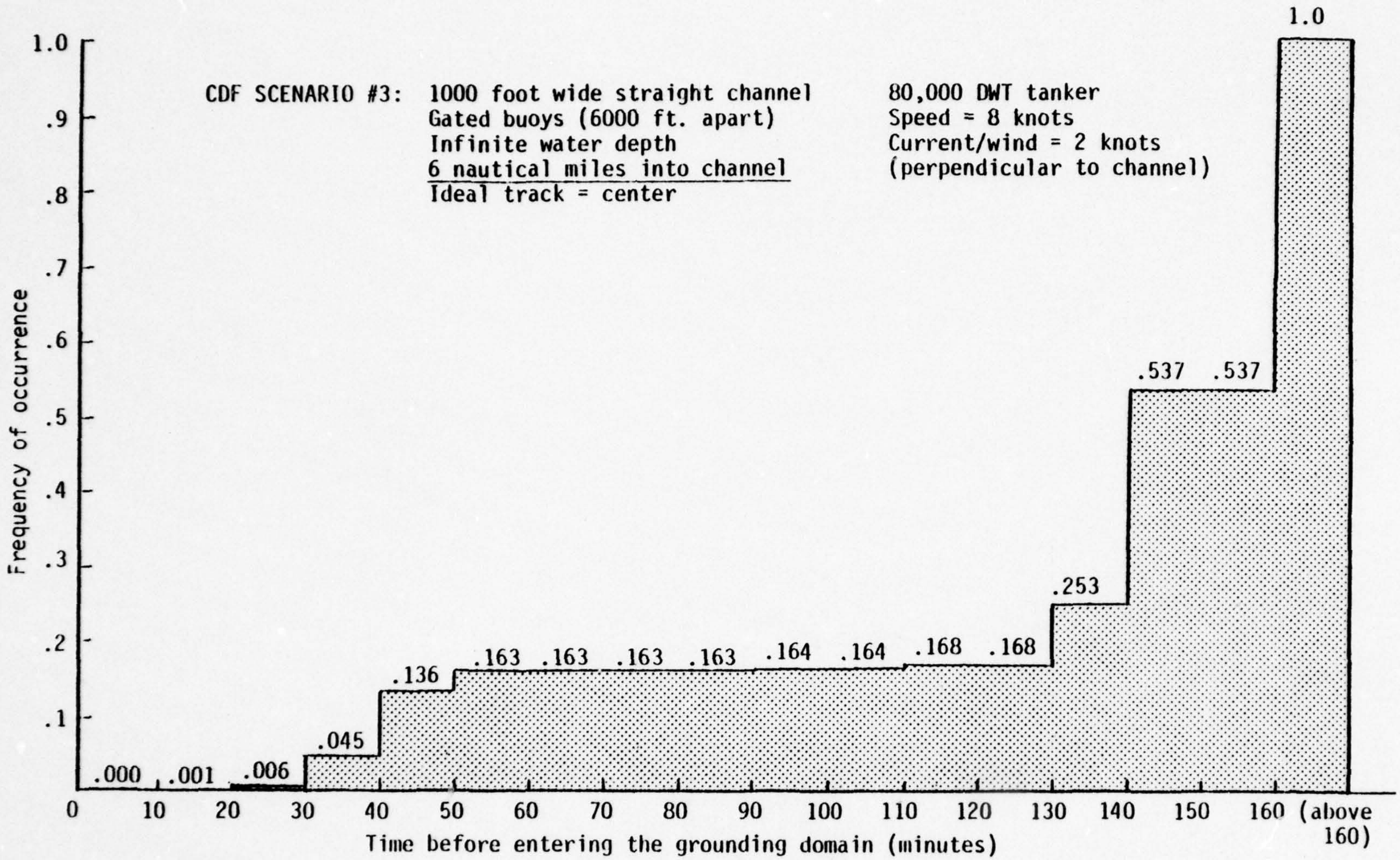

FIGURE B-47. CUMULATIVE PROBABILITY FOR PILOT DECISION TIMES, EXAMPLE #3.

9-75

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The gated buoys in our straight channel scenario provide pilots sufficient perceivable information to correct large errors in directions of motion upon entry into the channel. Figure B-48 shows an example of the frequencies of ships traveling through our defined scenario within 30 minutes of their grounding domain. It shows clear improvement in the pilot decision times as the vessels traverse the channel. At the 1 nautical mile mark (into the channel), 31.6 percent of vessels were traveling within 30 minutes of their grounding domain and after 10 nautical miles none of the vessels were traveling within 30 minutes of their grounding domain.

Results that compare different aids to navigation systems as alternatives are presented in exhibits 1 through 17 at the end of this Appendix.

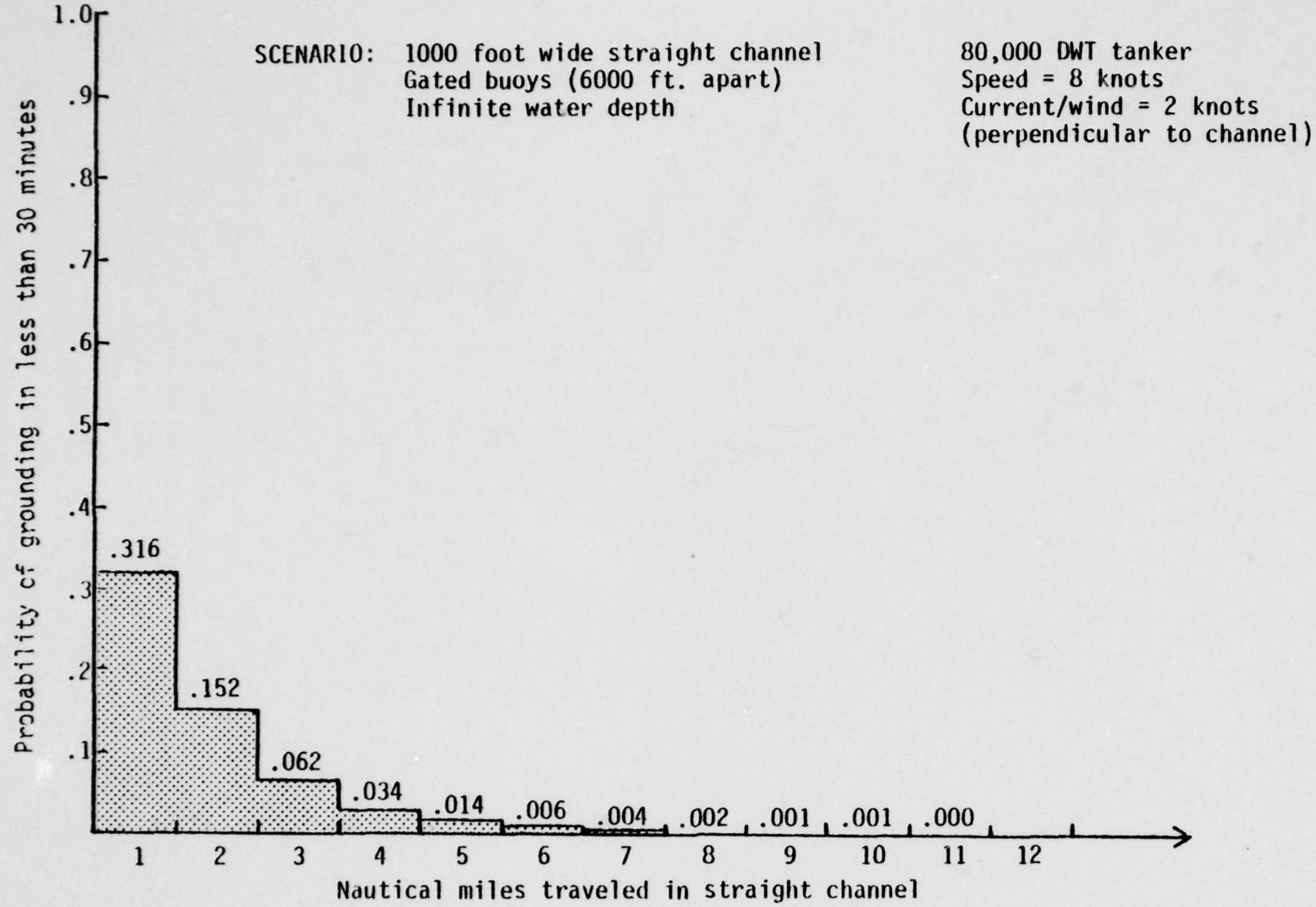

FIGURE B-48. REDUCTION OF RISK EFFECTIVENESS FOR GATED BUOYS

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2.0 Traffic Facilitation Index

Factors which contribute to traffic facilitation include harbor improvements (e.g., widening of channels) and vessel traffic services, as well as aids to navigation. However, we are concerned with the evaluation of aids to navigation and the proposed index is limited to that contribution.

The facilitation index is the product of two factors: an availability index and a transit time index.

Availability Index

The availability index is the ratio A_i/A_o, where A_o is the number of hours per base period (say, one year) in which a vessel of the type under consideration could safely transit a harbor segment if the mariner had perfect knowledge of the navigation parameters, and A_i is the number of hours per base period in which the same vessel type could safely transit the segment using only the information provided by the system of aids to navigation. The indices for a particular segment may be derived for a single vessel type or may be expressed as a weighted average for several vessel types of interest.

A_o will be the duration of the base period, minus those intervals in which the height of the tide precludes safe passage of the vessel, or does not permit sufficient clearance to satisfy a minimum bottom clearance regulation. For those periods when tidal height is adequate, intervals when combinations of wind and current preclude safe passage will also be subtracted.

A_i will be equal to A_o minus any other intervals in which safe transit, using navigation parameters derived from the system of aids under consideration, is not possible. To derive A_o, it will be necessary to apply the distribution of tides and currents, the correlations of which are usually well known, and of wind. The highly aggregated meteorological data that are readily available for most areas will not

usually permit the derivation of correlation factors for wind and current. However, in most areas winds can be treated as an independent variable (allowances will have to be made for those bodies of water in which wind-driven currents significantly modify tidal effects). In addition, the computation of A_i will require the distributions of brightness (a trivial task) and visibility conditions, and where applicable, their correlation factors. Preliminary efforts may treat the correlation of brightness with any other ambient condition as random (this neglects the sea breeze and land breeze effects). In many areas, fog or haze-caused low visibility will correlate with wind conditions and brightness.

Transit Time Index

The transit time index is the ratio t_i/t_o, where t_o is the time required for transit of the segment with perfect knowledge of all pertinent navigational parameters and t_i is that required for transit with the information derived from the system of aids to navigation.

There are two factors which may affect transit time under those conditions when safe transit is possible:

a. With perfect knowledge of his navigation parameters, the mariner would follow an ideal track which provided the desired margin of safety, and which therefore represented the shortest route without sacrifice in safety. With less than perfect knowledge, the vessel would deviate from that track somewhat, or a modified track providing larger margins (to compensate for uncertainties) would be followed.

b. The speed at which a mariner would proceed through restricted waters may be influenced by his confidence in the navigation parameters.

In most harbors and waterways, it is apparent that the foregoing factors will be of small consequence. Relatively large derivations from the ideal track, within the confines of the waterway, would be unlikely to increase the track length by more than a few percent. In coastal

navigation, or in the transit of broad waterways, the track length differences may be significant. The tendency of a mariner to reduce speed when he has less than perfect knowledge of his navigation parameters is postulated, but at this time is without basis for quantification. Future pilot interviews should be structured to acquire objective data.

A simplified example of the computation of the availability index is shown in Tables B-4a and B-4b. The ambient factors for brightness, visibility and set-and-drift vector were assumed to be randomly correlated with tidal height.

HYPOTHETICAL EXAMPLE (ONE YEAR BASE PERIOD)

CONSTRAINT	VALUE	FACTORS WHICH PRECLUDE MIN.	% OF TIME FACTORS
Minimum Bottom Clearance	2.5'	Tidal Stage	2.1%
Minimum Clearance to Grounding Constraint	40'	Set and Drive Vector ≥ 3 Knots	0.15%

$$A_o = 8760\left\{1 - \left|.021+.0015-(.021x.0015)\right|\right\}^* = 8563$$

* Assumes that correlation is random.

TABLE B-4a. HYPOTHETICAL EXAMPLE, CALCULATION OF A_o

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HYPOTHETICAL EXAMPLE (Sheet 2)

CONDITIONS WHICH PRECLUDE MAINTENANCE OF MINIMUM CONSTRAINTS USING A/N SYSTEM

BRIGHTNESS (%)	VISIBILITY	SET & DRIFT VECTOR (%)
Day (50)	< 0.8 n. mi. (0.8)	Any (100)
Day (50)	0.8 to 1.5 n. mi. (1.0)	≥ 1.5 Knots any direction (1.9)
Day (50)	≥ 1.5 n. mi. (98.2)	1.5 to 2.5 Knots any (4)
Night (50)	< 1.5 n. mi. (1.8)	Any (100)
Night (50)	≥ 1.5 n. mi. (98.2)	1.5 Knots any direction (4)

$$A_i = A_o\left\{1 - 0.5\left[.008+(.01x.019)+(.982x.04)+.018+(.982x.04)\right]\right\}$$

$$= A_o \times .948 = 8114.5$$

Availability Index = 8114.5/8563 = .948

TABLE B-4b.

IV. COMPARATIVE RESULTS

Introduction

The preliminary results for various aid to navigation systems are shown at the end of this section in Exhibits 1 through 17. A summary table of these outputs is shown in Table II-1. The model outputs shown in the exhibits are:

1. Cross-track position contours
2. Direction of motion contours
3. Improvement in pilot decision times.

The interrelationships of these three outputs with the particular aid to navigation system being utilized by the pilots provides insight into the effectiveness of that aid to navigation system. Comparison of the three model outputs described above for various identical desired tracks, while maintaining the ship type, ship speed, environmental conditions, waterway geometry, etc., shows the effect of the information provided by different aids to navigation systems. In a similar way, the model was shown to be sensitive to ship type, desired track of the vessel, visibility, and the pilot indifference zone. The corresponding c_p maps used for the exhibited cases are shown in the figures listed below:

Gated Buoys (Cases 1,2,3,17)	Figure B-20.a
Buoys One Side (Cases 4,5,11,12)	Figure B-21.a
Range Only (Cases 6,7,8)	Figure B-22.a
Range/Buoys One Side (Cases 9,10)	Figure B-23.a
Radar (Case 15)	Figure B-25.a
LORAN-C (Case 16)	Figure B-26.a
Buoys One Side/Poor Visibility (Cases 13,14)	Figure B-24.a

For convenience of the reader, these figures are shown right after the exhibits in this section.

The preliminary results shown in Exhibit 1 for gated buoys will be used to illustrate interpretations that can be made from the

model output. The buoys shown are symbolic of buoys located on the channel edge. Buoys are located on both sides of the channel and the buoys are gated. This information is shown to allow correlation of the changes in models output to the aid to navigation system. Runs were initiated with 1000 vessels whose directions of motion were uniformly distributed from .2 degrees to the left (top of figure) to 3.4 degrees to the left. The initial cross-track positions of all runs were uniformly distributed from 50 feet to the left of the ideal track to 50 feet to the right of the desired track. All cases were run at 8 knots initial speed, indifference zones of 25 feet, ship type of 80,000 DWT tanker, unless otherwise specified in the exhibit.

The cross-track information is displayed as probability contours. The dashed curves in Exhibit 1 bound 98 percent of the cross-track positions that vessels could maintain while traversing a channel of this size. The solid curves in Exhibit 1 bound 80 percent of the cross-track positions that vessels could maintain while traversing a channel of this size. The initial conditions could result in a transient region for cross-track position and direction of motion until the pilots perceive their cross-track positions as being incorrect and change their course. Several course changes may be required before this transient region is damped by the information from the aid to navigation system. The time period or distance that is required to reduce the initial transient to zero is referred to as the transient portion of our output. This transient portion characterizes the effectiveness of the information from the A/N system to dampen incorrect directions of motion. For the gated buoy case, the transient portion of the run damps to steady-state at about 2 nautical miles. The transient region will be used when comparing different A/N systems.

The portion of the run after 2 nautical miles shows a rather steady pattern for cross-track position as well as directions of motion. This portion of the run will be called the steady-state portion of the run. The portion of the run will be used to compare different A/N systems.

The direction of motion contours are analogous to the cross-track contours. The dashed curves bound 98 percent of the directions of motion, while the solid curves bound 80 percent of the directions of motion. This information can be used to correlate changes in direction to the information in the A/N system.

The degree of improvement in pilot decision times is also shown in each exhibit and will be used to compare different A/N systems.

Gated Buoy vs Range Comparison

The first comparison to be made will be utilization of gated buoys for traversing a desired track down the center of the straight channel as compared to a range. The gated buoys are spaced every nautical mile. The front range beacon is located 6 miles from the starting location of the vessel, and the beacon spacing is 1 mile.

Exhibit 1, Gated Buoys. The cross-track positions stabilize after a transient distance of about 2 nautical miles. There appears to be no noticeable effect when passing a buoy; this results from modeling visual angle matching as the observable in the center of the channel. The magnitude of the 98 percent bound for directions of motion is $\pm 4^{\circ}$. This is due to the cross-track distance at which the pilot perceives his cross-track position as being incorrect. The 98 percent bound on cross-track positions stabilizes at $\pm$ 80 feet. The risk level is maintained at less than 10 percent of the vessels with pilot decision times less than 15 minutes.

Exhibit 6, Range Only. The cross-track positions improve as the vessels approach the range. The magnitude of the 98 percent bound for cross-track positions decreases to $\pm$ 30 feet as the vessels approach the range. The magnitude of the 98 percent bound for directions of motion improve as the vessels approach the range due to improved cross-track information. The number of vessels having pilot decision times less than 15 minutes decreases as the vessels approach the range.

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Pilot Indifference Comparison

Different pilots have different cross-track locations away from the ideal track at which they choose to change their direction of motion so as to return to their desired track. The first exhibit discussed below illustrates the results when a pilot does not correct until he perceives his location as being 25 feet from his desired track. The second exhibit discussed below illustrates the results when a pilot corrects whenever he perceives his location to have deviated from the desired track by any amount.

Exhibit 1, 25 Foot Indifference. The cross-track positions stabilize after a transient distance of about 2 nautical miles. There appears to be no noticeable effect when passing a buoy; this results from modeling visual angle matching as the observable in the center of the channel. The magnitude of the 98 percent bound for directions of motion is $\pm 4^0$. This is due to cross-track distance at which the pilot perceives his cross-track position as being incorrect. The 98 percent bound on cross-track positions stabilizes at $\pm$ 80 feet. The risk levels off, such that less than 10 percent of the vessels maintain pilot decision times less than 15 minutes.

Exhibit 2, 1 Foot Indifference. The cross-track positions stabilize in less than one nautical mile. There appears to be no noticeable effect on cross-track position when passing a buoy; this results from modeling visual angle matching when near the center of the channel. The magnitude of the 98 percent bound on directions of motion is slightly less than the 25 feet indifference case due to correcting as soon as the pilot perceives he is not on the desired track. The number of vessels having pilot decision times less than or equal to 15 minutes is maintained at less than 10 percent.

Visibility Comparison

The first exhibit discussed below has good visibility and the second exhibit only allows a buoy to be seen when the vessel is near the buoy along-track.

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Exhibit 11, Good Visibility. The cross-track contours remain somewhat stable after 2 miles. There is a correlation between improved cross-track position and passing a buoy. This is due to distance estimation to the buoy in the region 100 feet from the edge. Other less noticeable direction changes are taking place between buoys due to estimating cross-track position from the apparent slope of buoys ahead. The magnitude of the 98 percent direction of motion contour is larger for negative angles. This results from perceiving an error in cross-track position at a larger cross-track position from the desired track when the vessels have cross-track error toward the center of the channel. The correction angles to return to the desired track are large. The risk associated with traveling 100 feet from the edge of the channel is high. More than 40 percent of the vessels maintain pilot decision times of less than 15 minutes. This is due to the vessels traveling near the edge of the channel and traveling toward the channel edge when correcting from the center of the channel to the desired track.

Exhibit 13, Poor Visibility. The cross-track positions become a function of the number of buoys that are passed. There is improvement in the cross-track position contours when passing each buoy. This is because information concerning cross-track position is only available when passing a buoy by means of distance estimation. There is likewise a correlation between buoys and large directions of motion. These large directions of motion are due to corrections by those pilots that perceived their cross-track position to be in error and are returning to the ideal track. The risk associated with the poor visibility case is very high. The pilot decision times less than 15 minutes are low until the vessels pass the first buoy because all vessels are started with direction of motion away from the near edge. Upon passing the first buoy, 3000 feet, the high risk shown at 4500 feet is due to the large number of vessels now moving toward the nearest edge of the channel. About 50 percent of the vessels have pilot decision times of less than 15 minutes for the remainder of the track.

Ship Type Comparisons

The two ships used for comparisons are an 80,000 DWT tanker and a 250,000 DWT tanker. The difference in the two ships is reflected only in their grounding domains. The 250,000 DWT tanker requires more room for correcting errors in its direction of motion. The current run and observe model does not consider actual ship motion—this will be included in subsequent refinements of the model. Therefore, only the risk measure of pilot decision times shown in Exhibit 1 for an 80,000 DWT tanker and in Exhibit 17 for the 250,000 DWT tanker are discussed. The frequency of pilot decision times of less than 15 minutes is slightly higher for the 250,000 DWT tanker when traveling the middle of a straight channel. This difference is expected to become much greater when the ship's motion is incorporated into the straight channel run and observe model.

Reference Point Comparison

The two cases below have similar σ values along the selected desired tracks. The differences between the two cases is that gated buoys have two reference points. The first reference point to the left of the desired track is at the center of the channel when the observable is the matching of the visual angles formed by the gated buoys ahead. The second reference point is to the right of the desired track at the edge of the channel where ranging occurs on the buoys. The observable is the slope of the line connecting the buoys on the edge. These two reference points make the task of determining cross-track position psychologically easier when the vessel approaches the center of the channel and when the vessel gets near to the edge of the channel. There is no reference point for the LORAN-C case; the errors remain the same over the entire channel.

Exhibit 3, Reference Point. The cross-track contours reach steady-state at about 2 miles. There is no apparent correlation between passing a buoy and improved cross-track position. This is due

to modeling visual angle comparison at distances greater than 200 feet from the edge of the channel. The magnitude of the 98 percent cross-track contour reaches $\pm$ 100 feet. Large magnitudes for direction of motion contours are due to pilots having fairly large cross-track errors before perceiving their location to be incorrect. The frequency of pilot decision times less than 15 minutes is maintained at about 10 percent.

Exhibit 16, No Reference Point. The LORAN cross-track contours reach about $\pm$ 150 feet for the 98 percent contour. The additional 50 feet on each side is due to not having a nearby psychological reference point. In other words, the pilot's perception of cross-track position does not improve when the vessel moves either to the left or to the right of the desired track. The large magnitude for the 98 percent direction of motion contours is due to the pilots having locations far from the desired track when they perceive their location to be incorrect. The frequency of pilot decision times less than 15 minutes is maintained at about 10 percent (the desired track is center of channel).

At locations near the reference points, the gated buoy system provides more accurate information than does LORAN-C. The reference points occur at the center and the edge of the channel. Thus the improved information is provided where most needed to prevent grounding and to prevent crossing into the wrong side of the channel.

The risk measures of pilot decision time cannot be compared because the desired tracks are different.

TABLE B-5. DEFINITION OF CASES

CASE	AIDS TO NAVIGATION	MARINER'S DESIRED TRACK	COMMENTS
1. Gated buoys	Gated buoys, 1 n. mi. separation	Center of Channel	Since ideal track is center of channel, only zone one of Map is exercised.
2. Gated buoys	Same as above	Center of Channel	Indifference zone = 1 ft.
3. Gated buoys	Same as above	300 feet from left edge	
4. Buoys one side	Buoys one side 1 n. mi. separation	Center of Channel	
5. Buoys one side	Same as above	200 feet from edge marked with buoys	
6. Range	Range only	On-Range	All range cases run with 1 n. mi. between range marks.
7. Range	Range only	On-Range	Indifference zone = 1 foot.
8. Range	Range only	200 ft. off-range	
9. Range	Range plus buoys one side	On-Range	Buoys used by mariner only to establish on-track position.
10. Range	Same as above	200 ft. off-range	Same as above.
11. Buoys one side	Buoys one side 1 n. mi. separation.	100 ft. from edge marked with buoys.	
12. Buoys one side	Same as above	Same as above	Indifference zone = 1 foot.
13. Buoys one side	Same as above	Same as above	Poor visibility case: Information provided only when buoy is abeam.
14. Buoys one side	Same as above	Same as above	Poor visibility case. Indifference zone = 1 foot.
15. Radar PPI scope	Radar fixing on buoys on one side	Center of Channel	Radar uses information only from buoys on channel edge.
16. Loran - C	Loran - C	Center of Channel	σ reflects only short-term variable errors.
17. Gated buoys	1 n. mi. separation	Center of Channel	250,000 CWT Vessel

Initial Conditions: P distribution between ± 50 ft. of ideal track. θ distributed between .2 and 3.4 degrees. Indifference zones are 25 ft. except where indicated. Vessels used are 80,000 CWT except where indicated.

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Exhibit 1: Gated Buoys/Center of·Channel

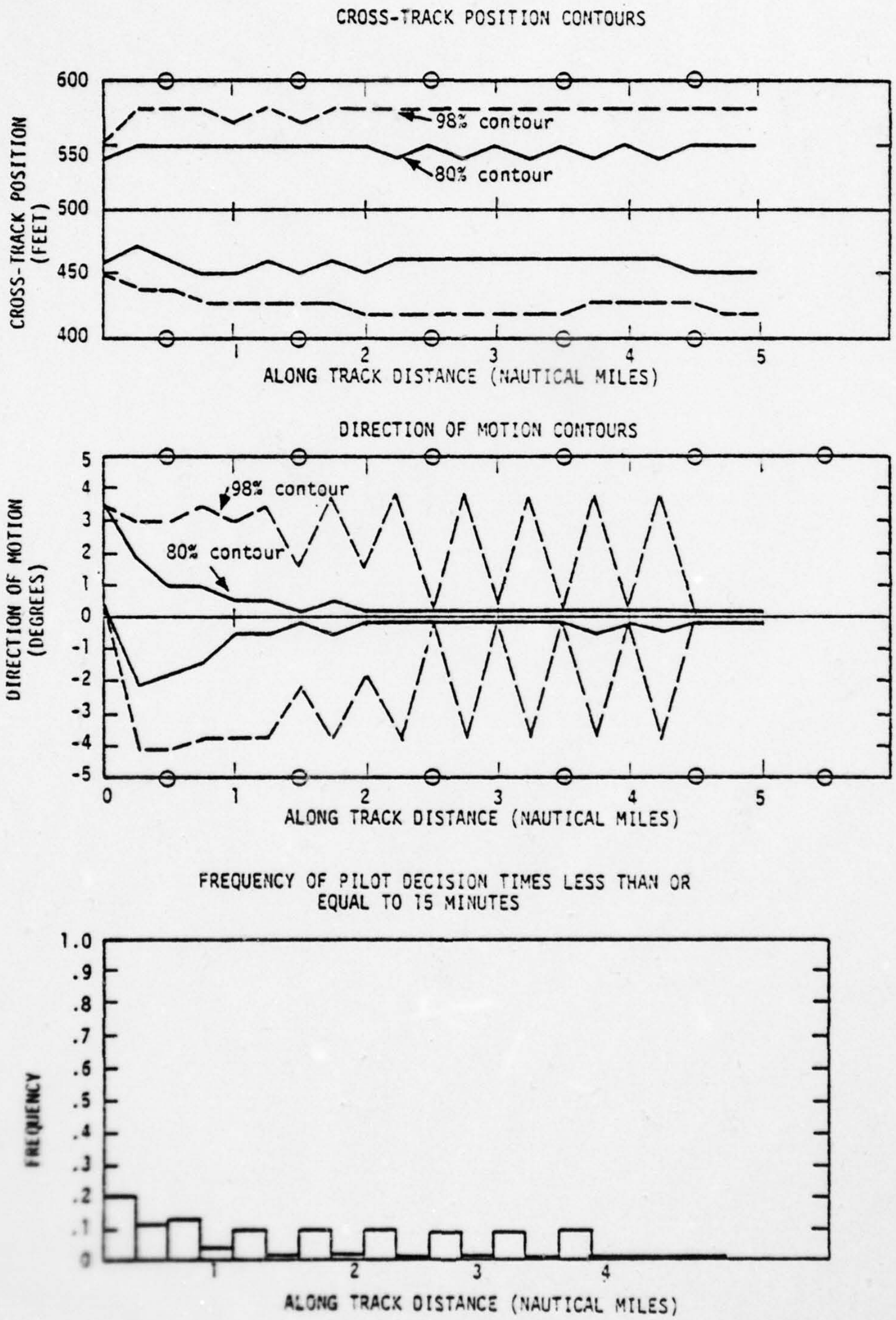

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Exhibit 2: Gated Buoys/Center of Channel
(Indifference Zone = 1 FOOT)

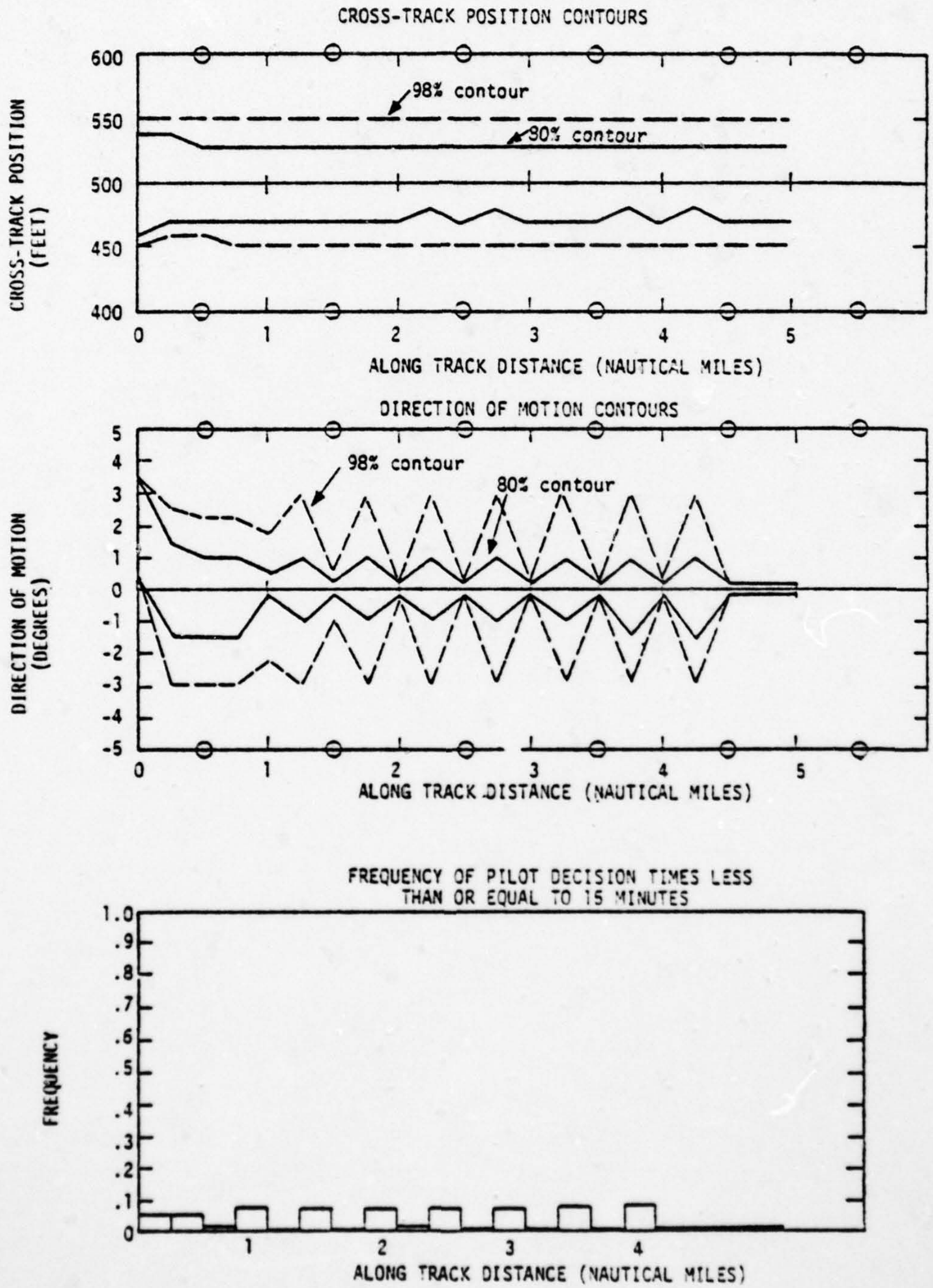


Exhibit 3: Gated Buoys/300 FT from Edge

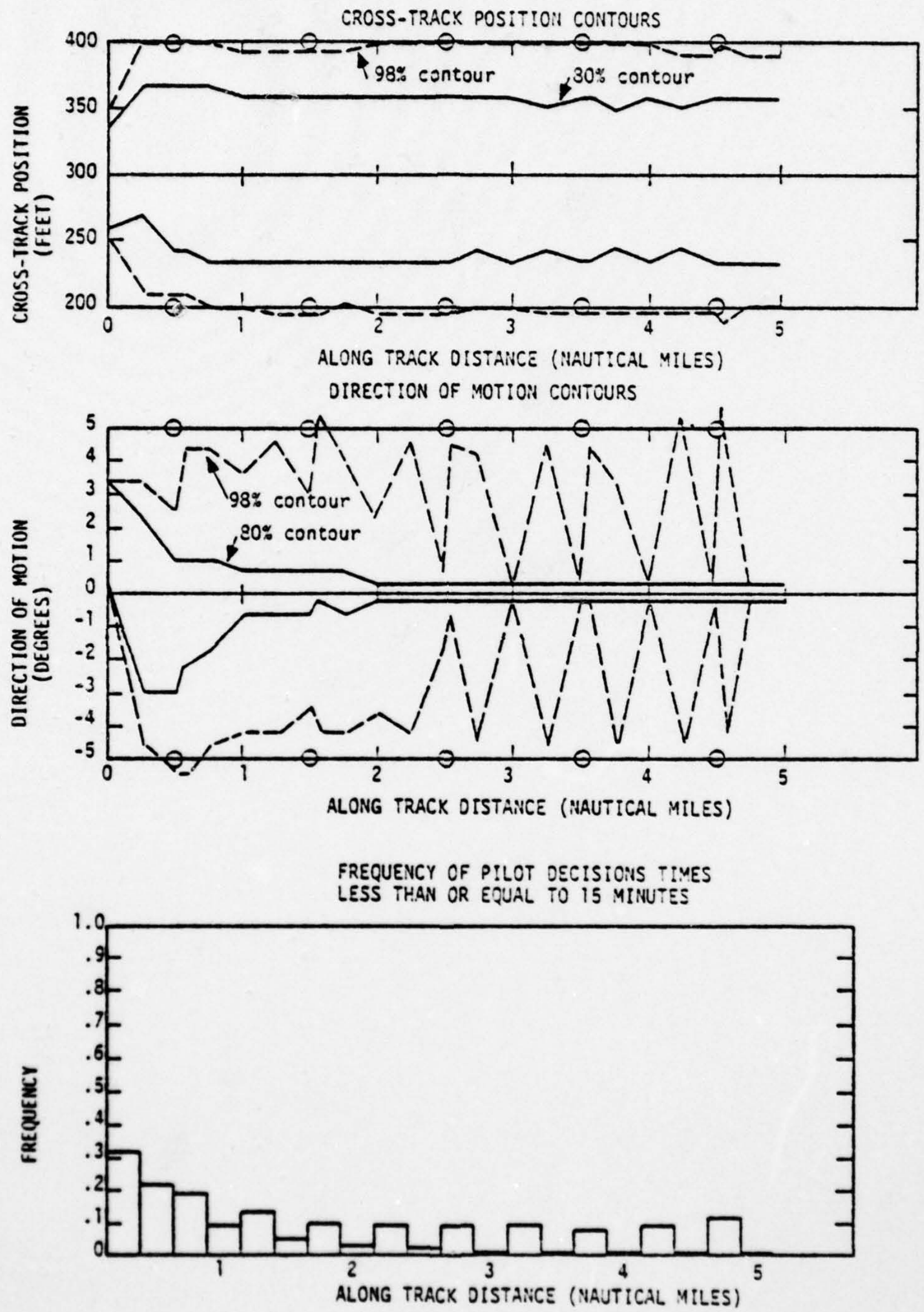
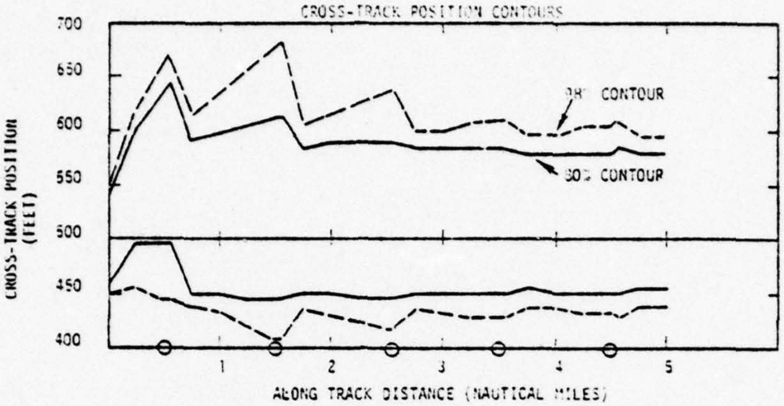
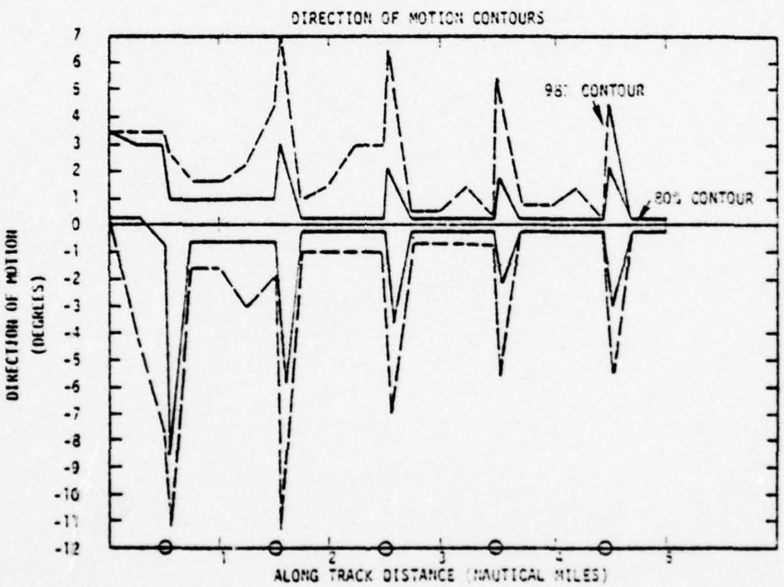


Exhibit 4: Buoys One Side/Center of Channel





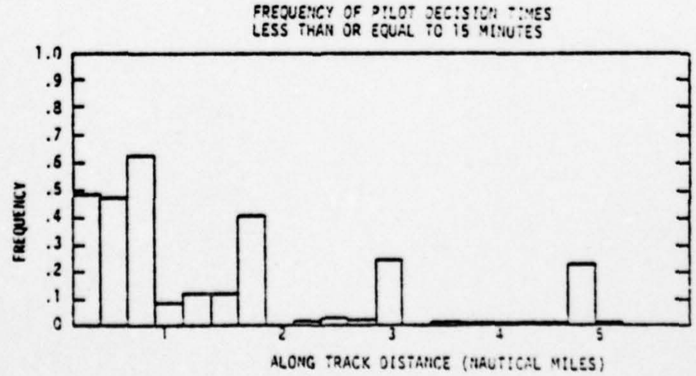


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Exhibit 5: Buoys One Side/200 FT from Edge

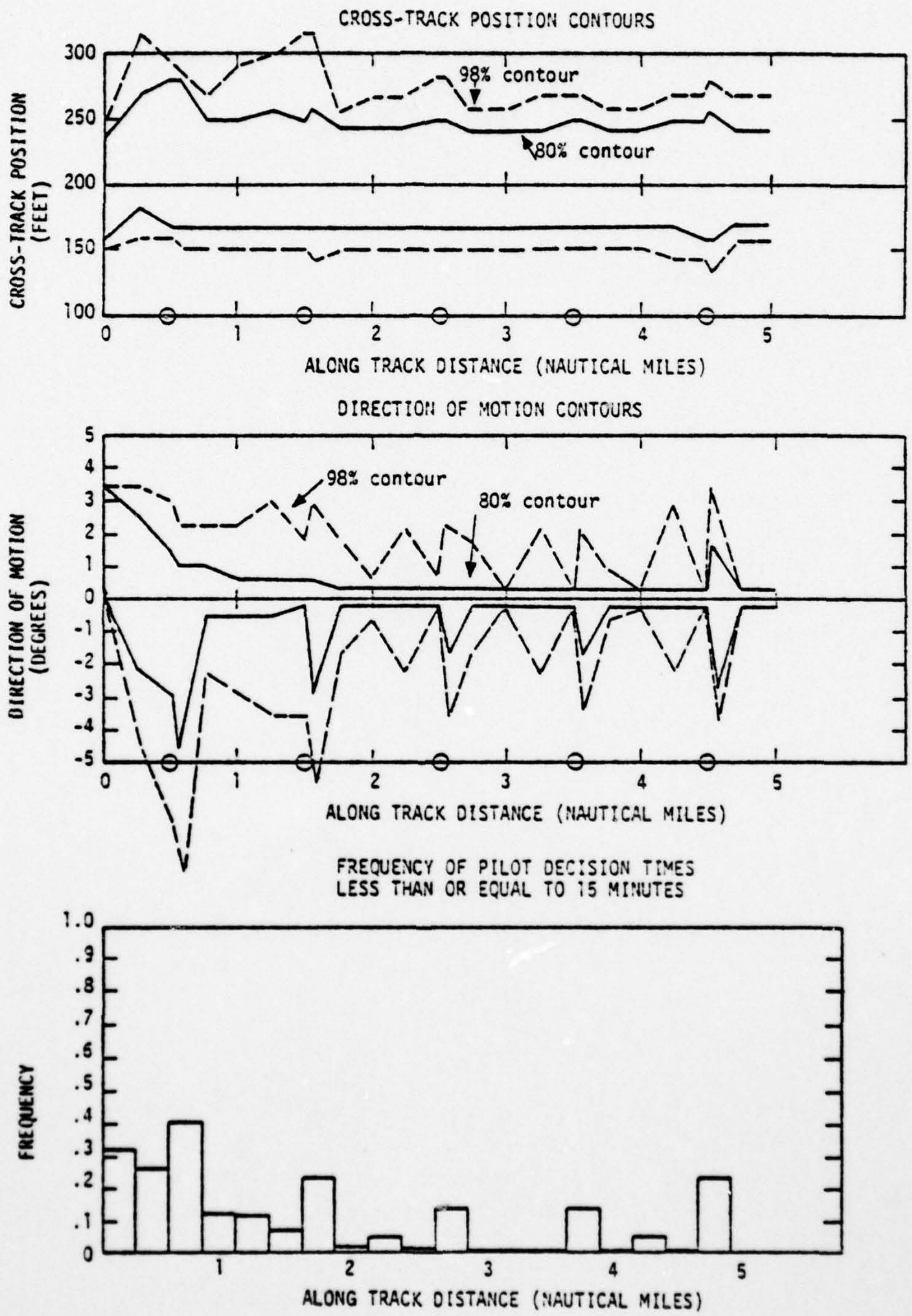

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Exhibit 6: Range/Center of Channel

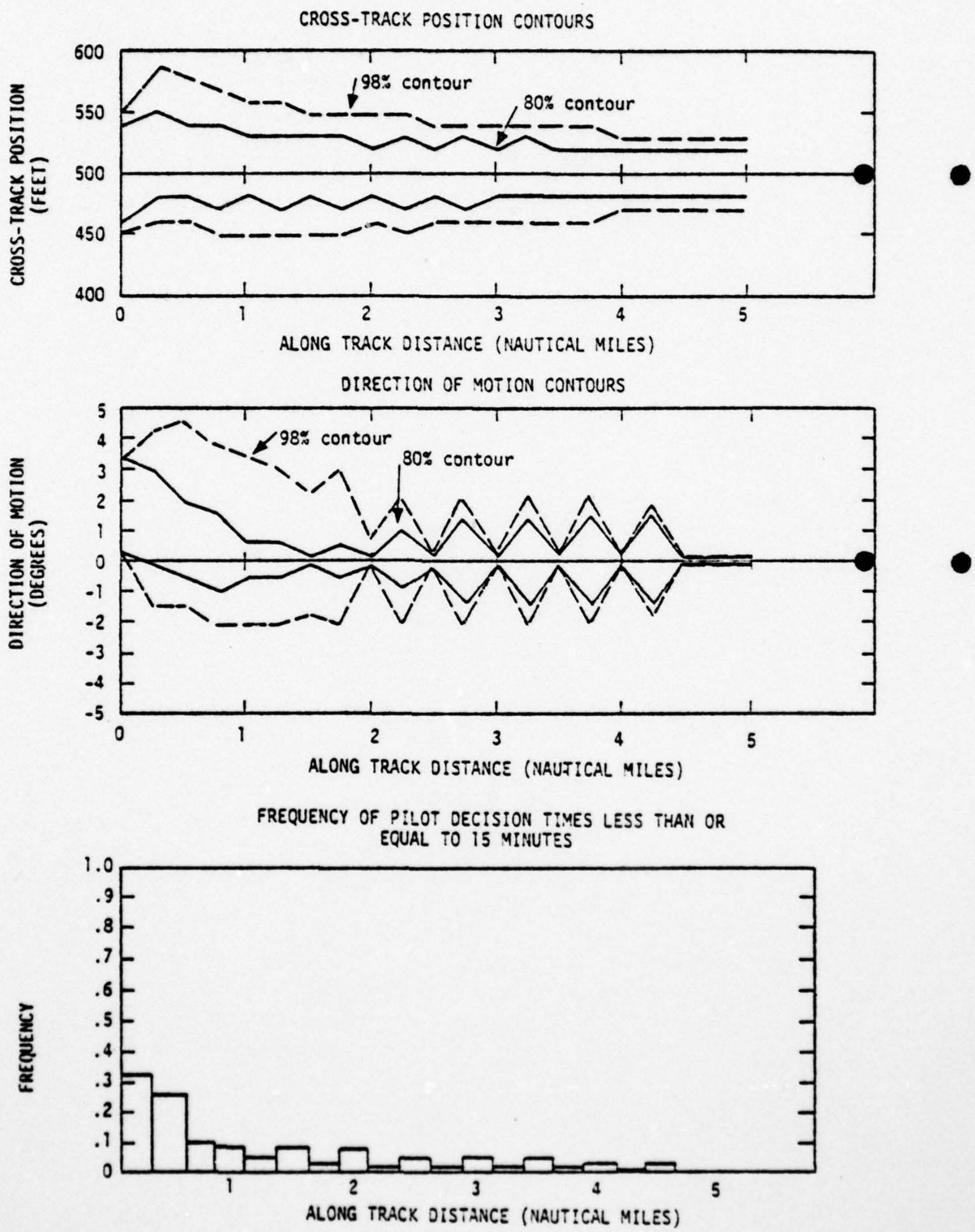
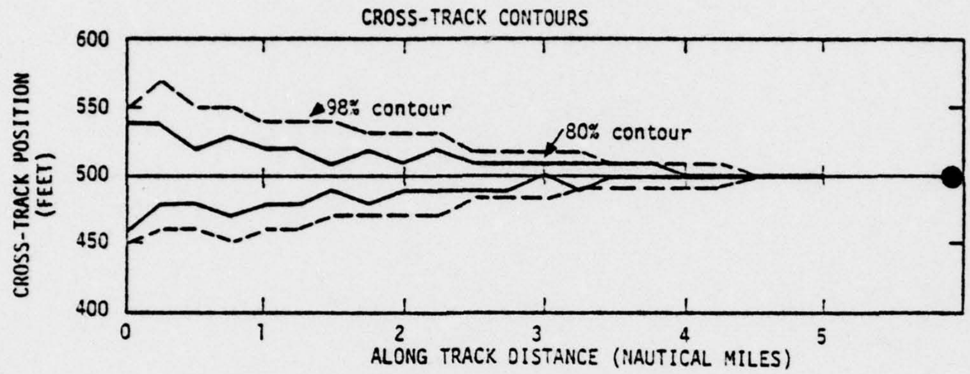
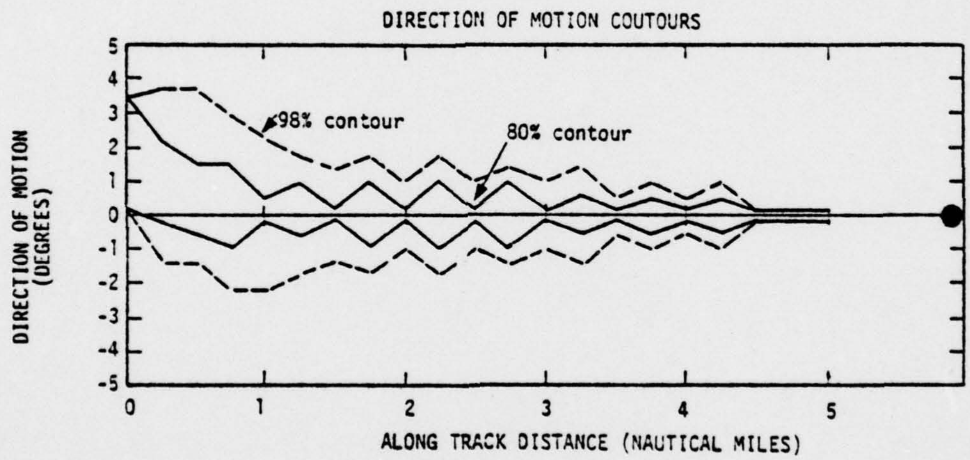


Exhibit 7: Range/Center of Channel
(Indifference Zone = 1 FOOT)





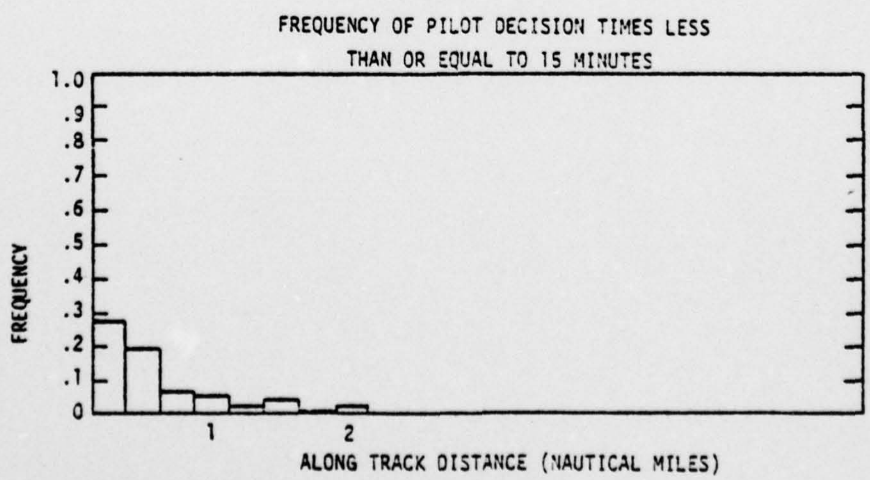


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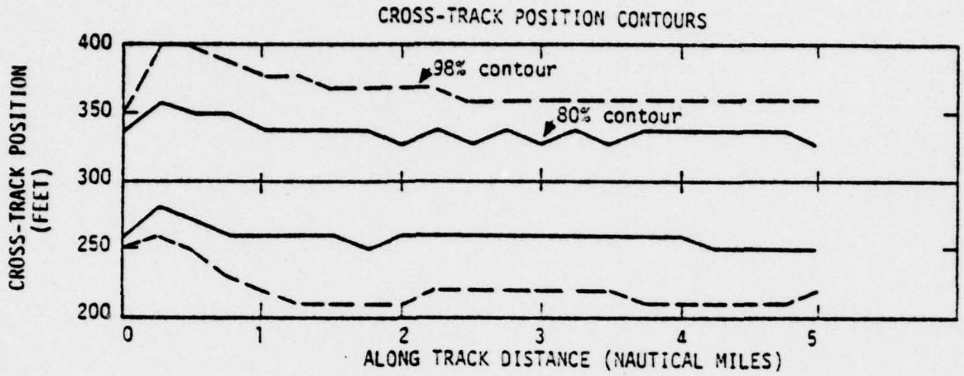
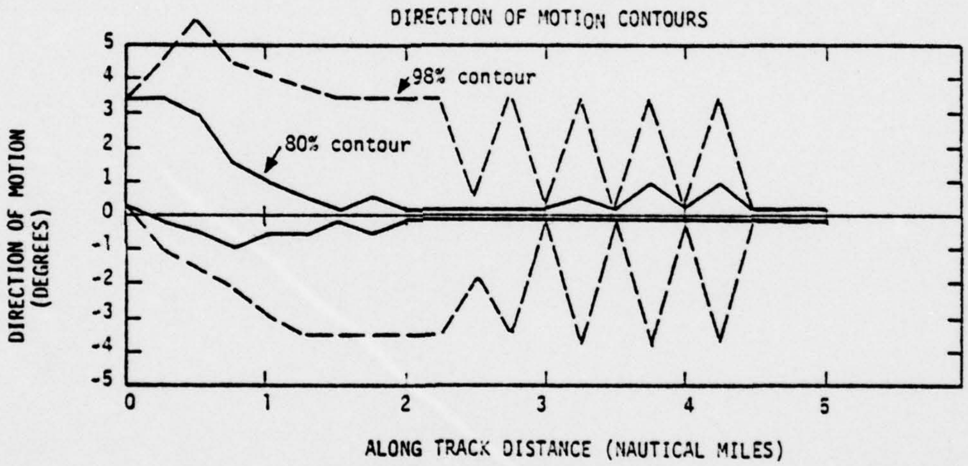
Exhibit 8: Range/300 FT from Edge





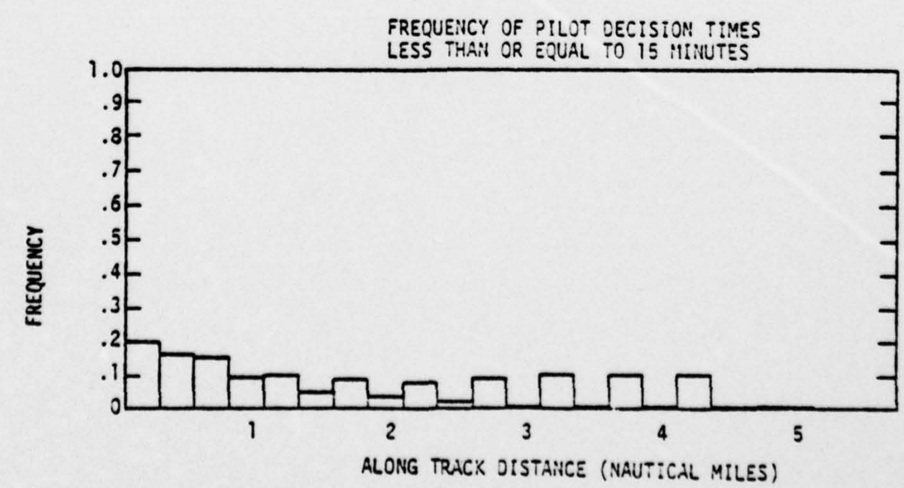
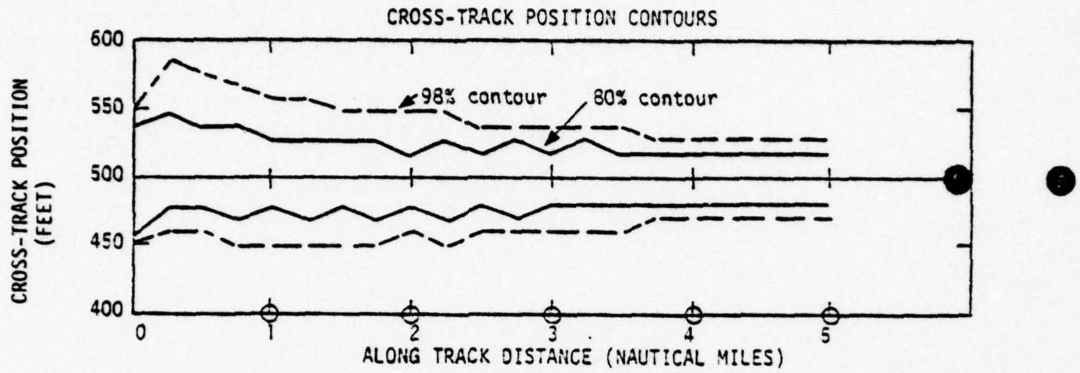
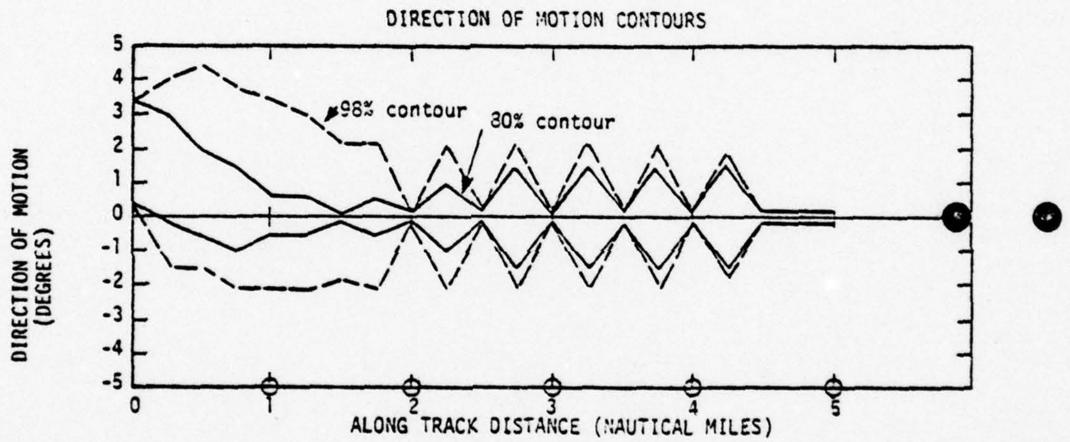


Exhibit 9: Range with Buoys/Center of Channel





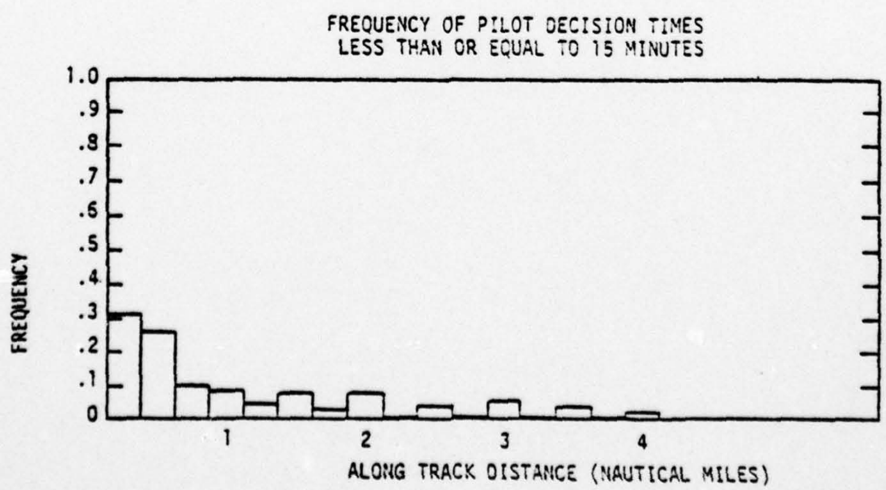


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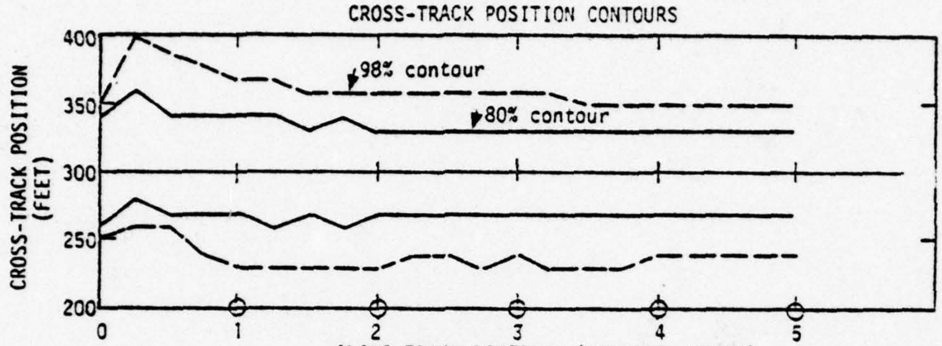
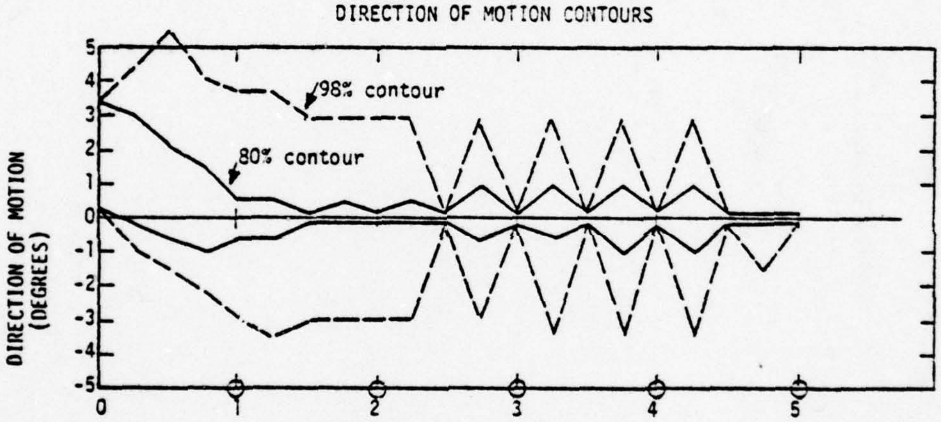
Exhibit 10: Range with Buoys/300 FT from Edge

CROSS-TRACK POSITION CONTOURS



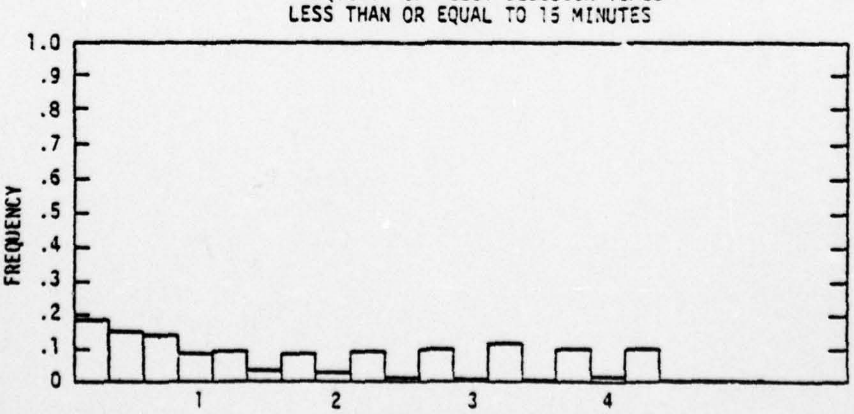
ALONG TRACK DISTANCE (NAUTICAL MILES)

DIRECTION OF MOTION CONTOURS



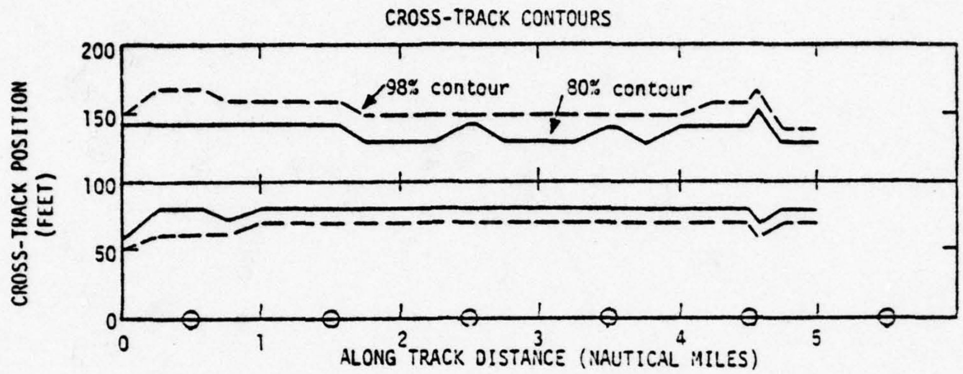
ALONG TRACK DISTANCE (NAUTICAL MILES)

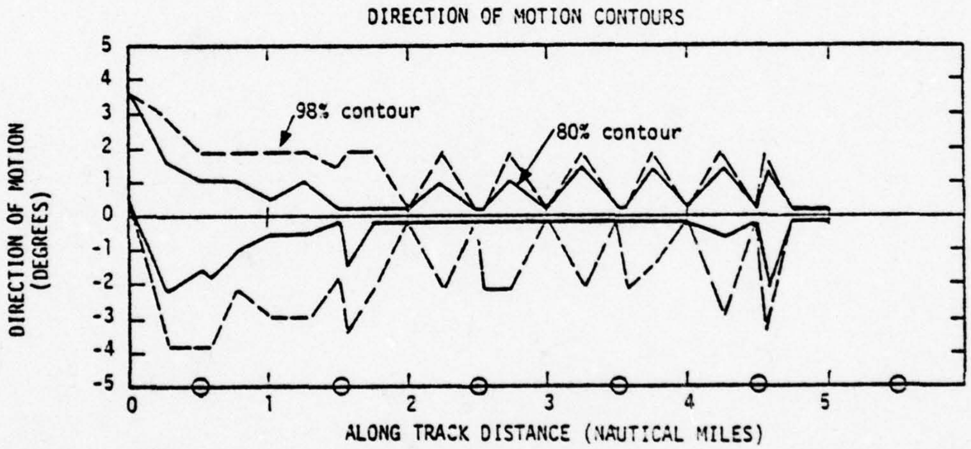
FREQUENCY OF PILOT DECISION TIMES
LESS THAN OR EQUAL TO 15 MINUTES



ALONG TRACK DISTANCE (NAUTICAL MILES)

Exhibit 11: Buoys One Side/100 FT from Edge





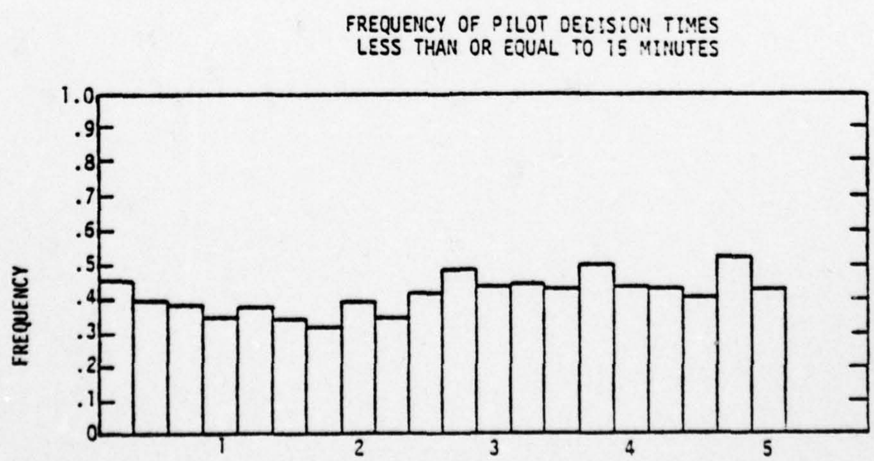


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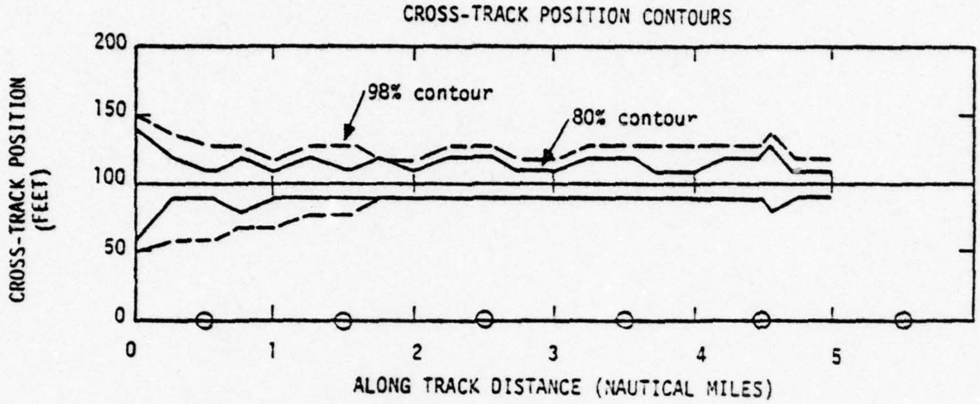
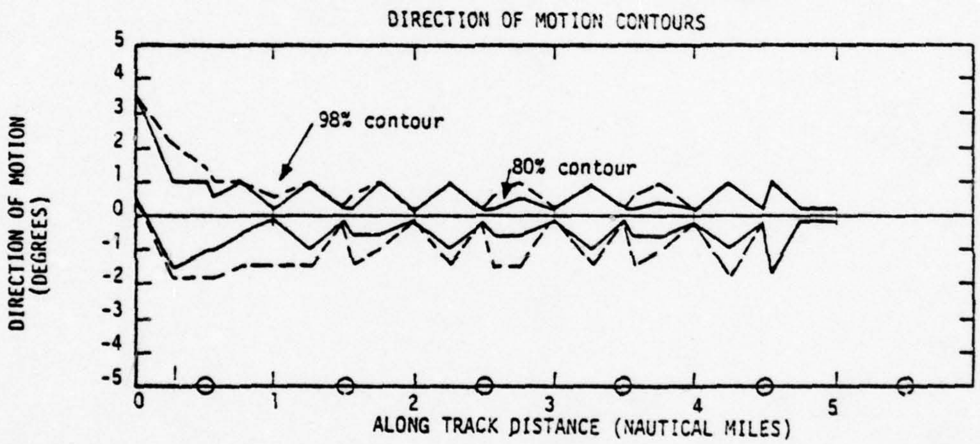
Exhibit 12: Buoys One Side/100 FT from Edge
(Indifference Zone = 1 FOOT)





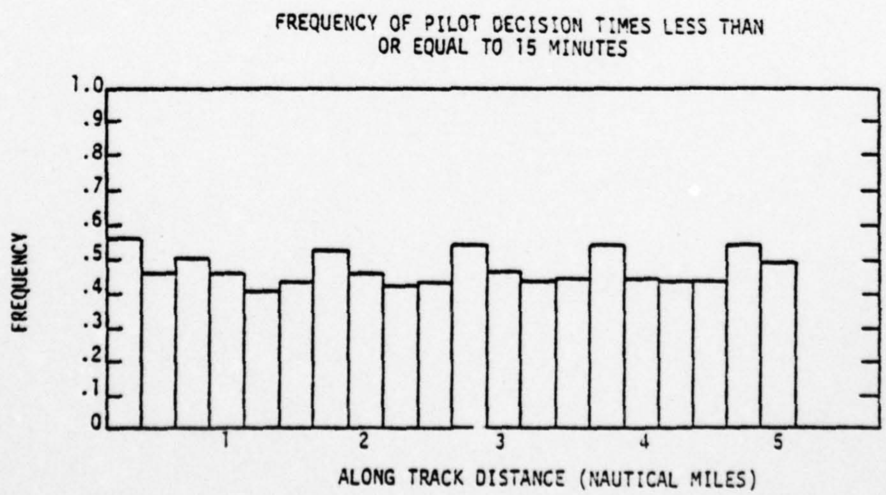


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Exhibit 13: Buoys One Side/100 FT from Edge/Poor Visibility

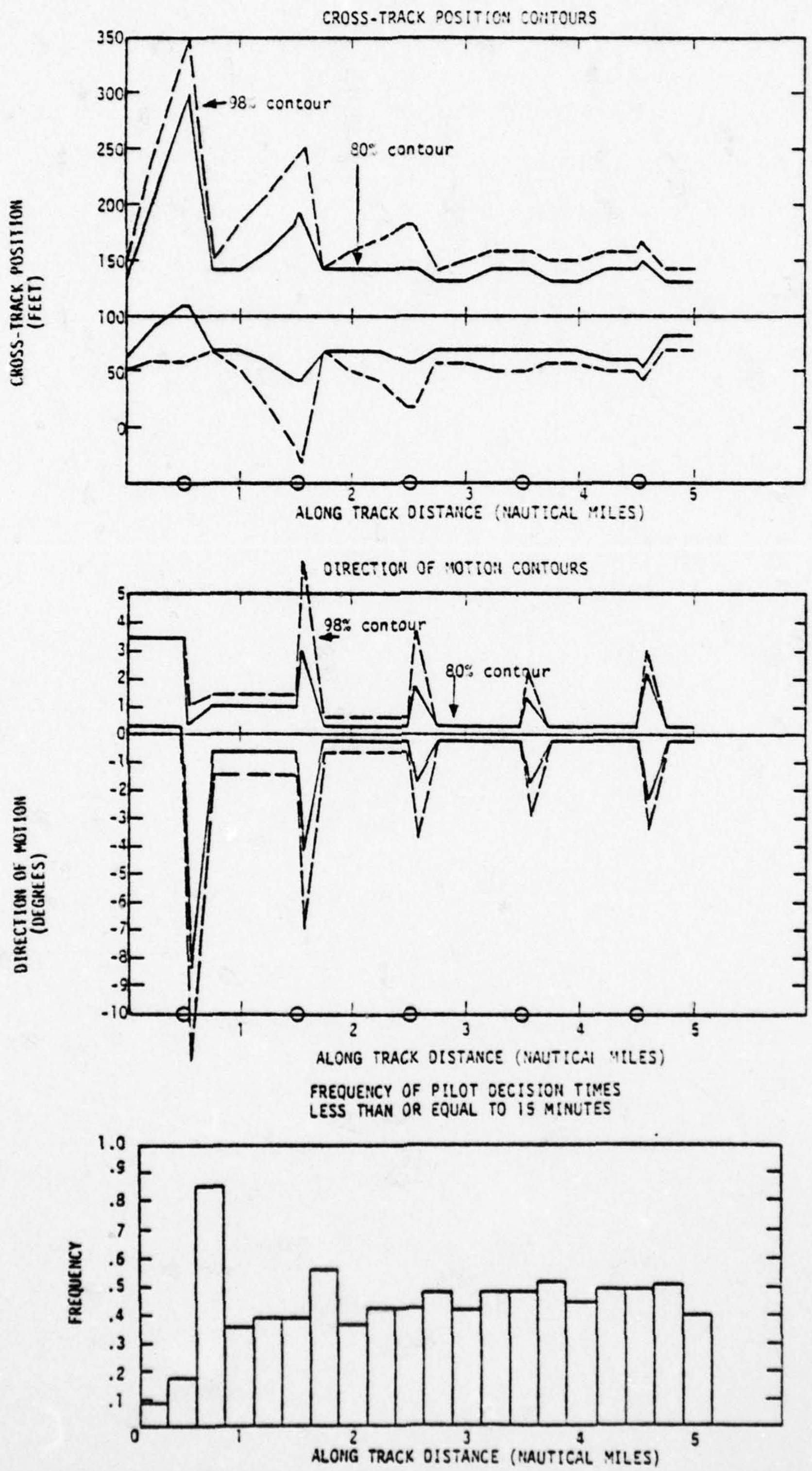

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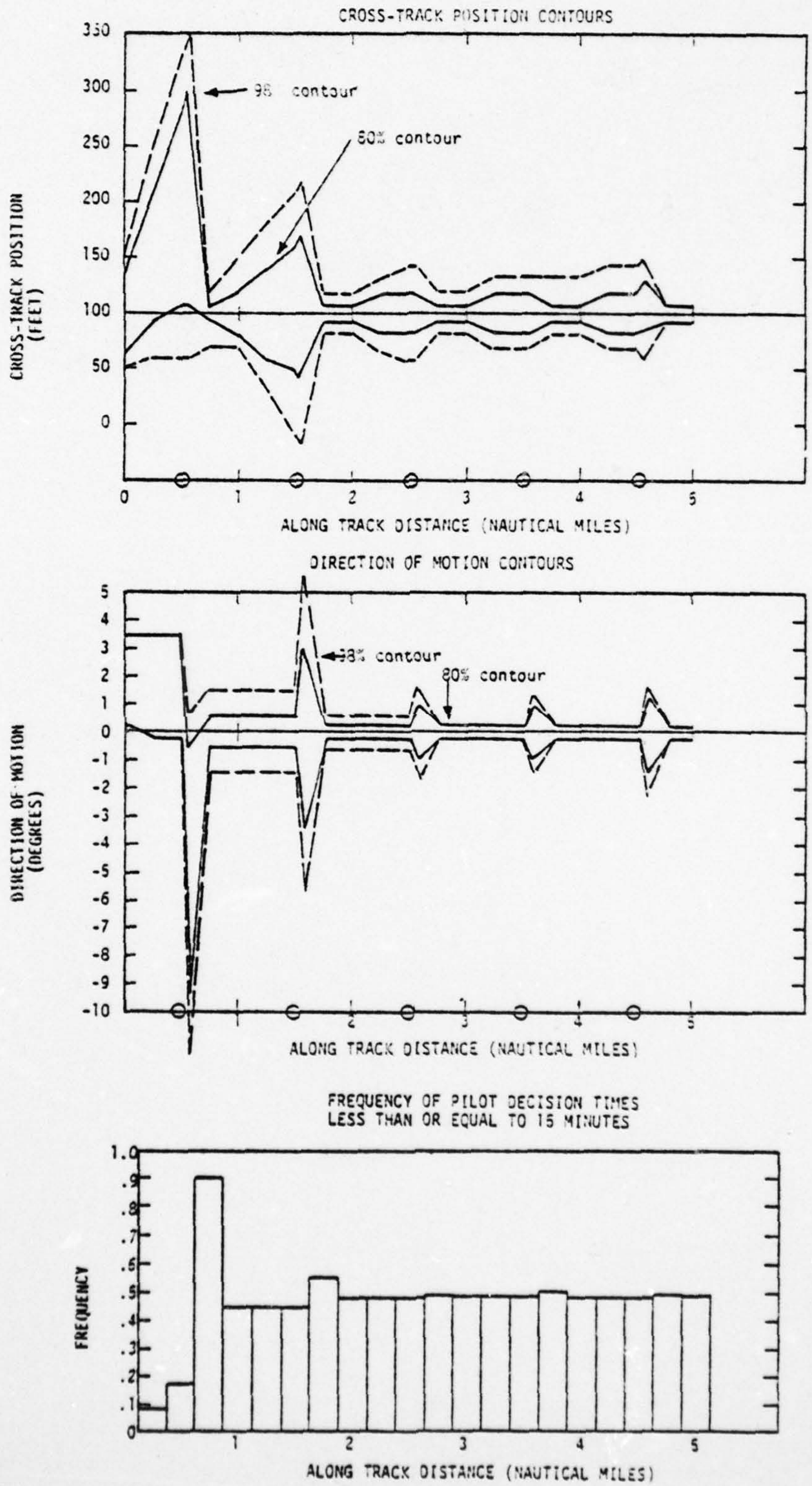
Exhibit 14: Buoys One Side/100 FT from Edge/Poor Visibility
(Indifference Zone = 1 Foot)



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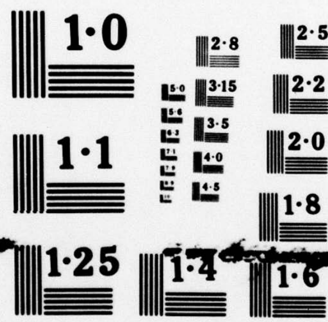
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4·5
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1·25
1·4
1·6

Exhibit 15: Radar/Center of Channel

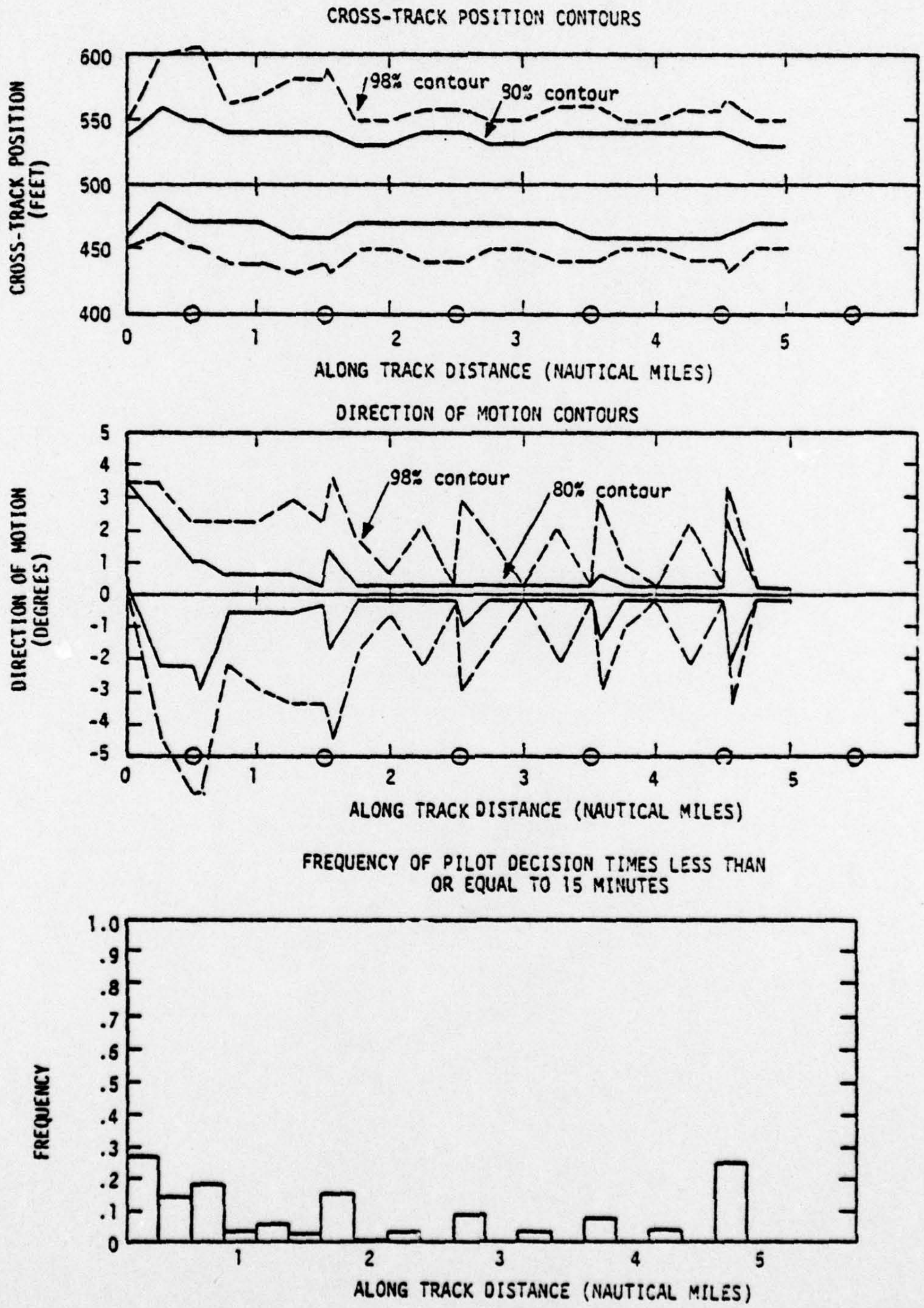

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Exhibit 16: LORAN-C/Center of Channel

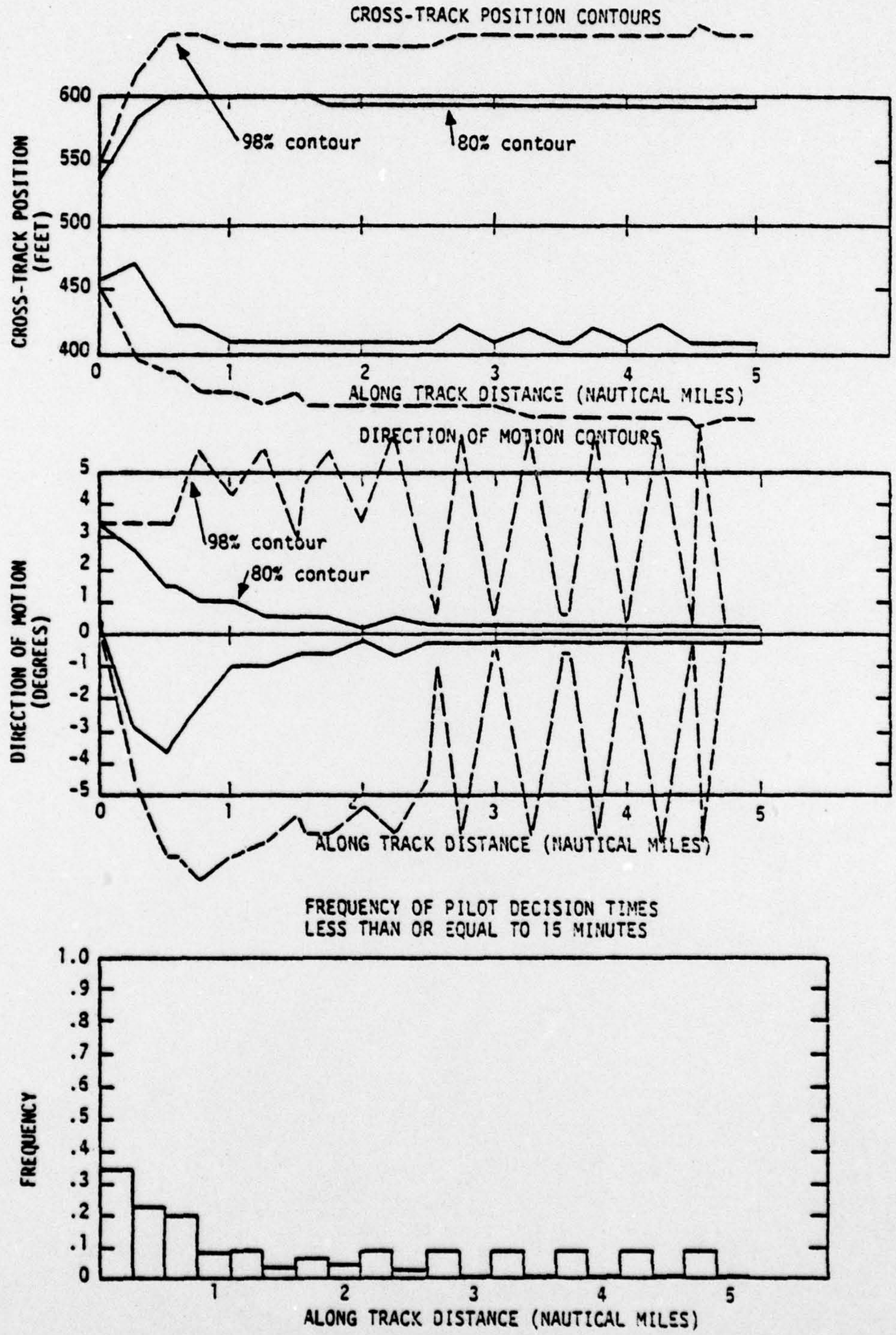

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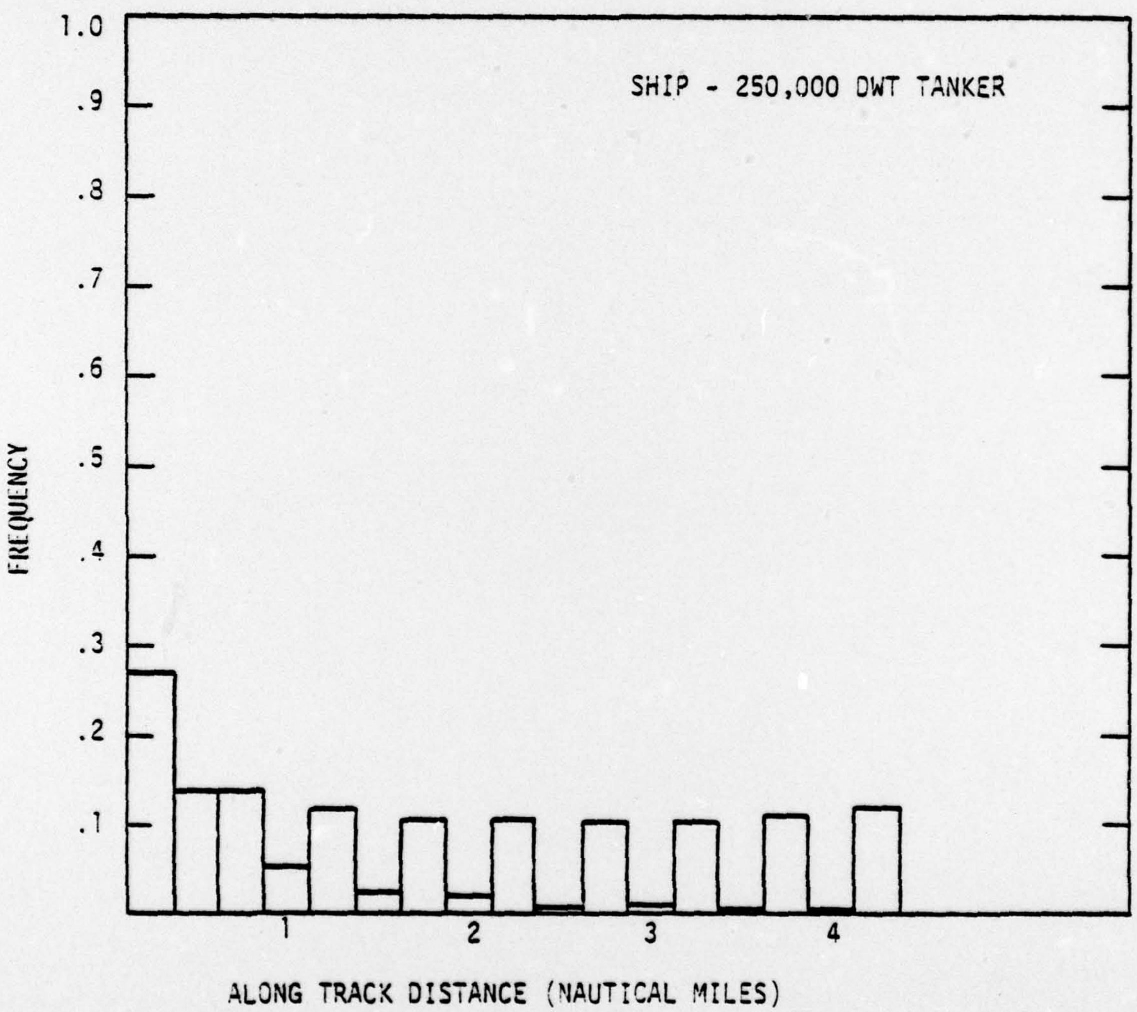
Exhibit 17: Gated Buoys/Center of Channel
250,000 DWT tanker

FREQUENCY OF PILOT DECISION TIMES LESS THAN OR EQUAL TO 15 MINUTES



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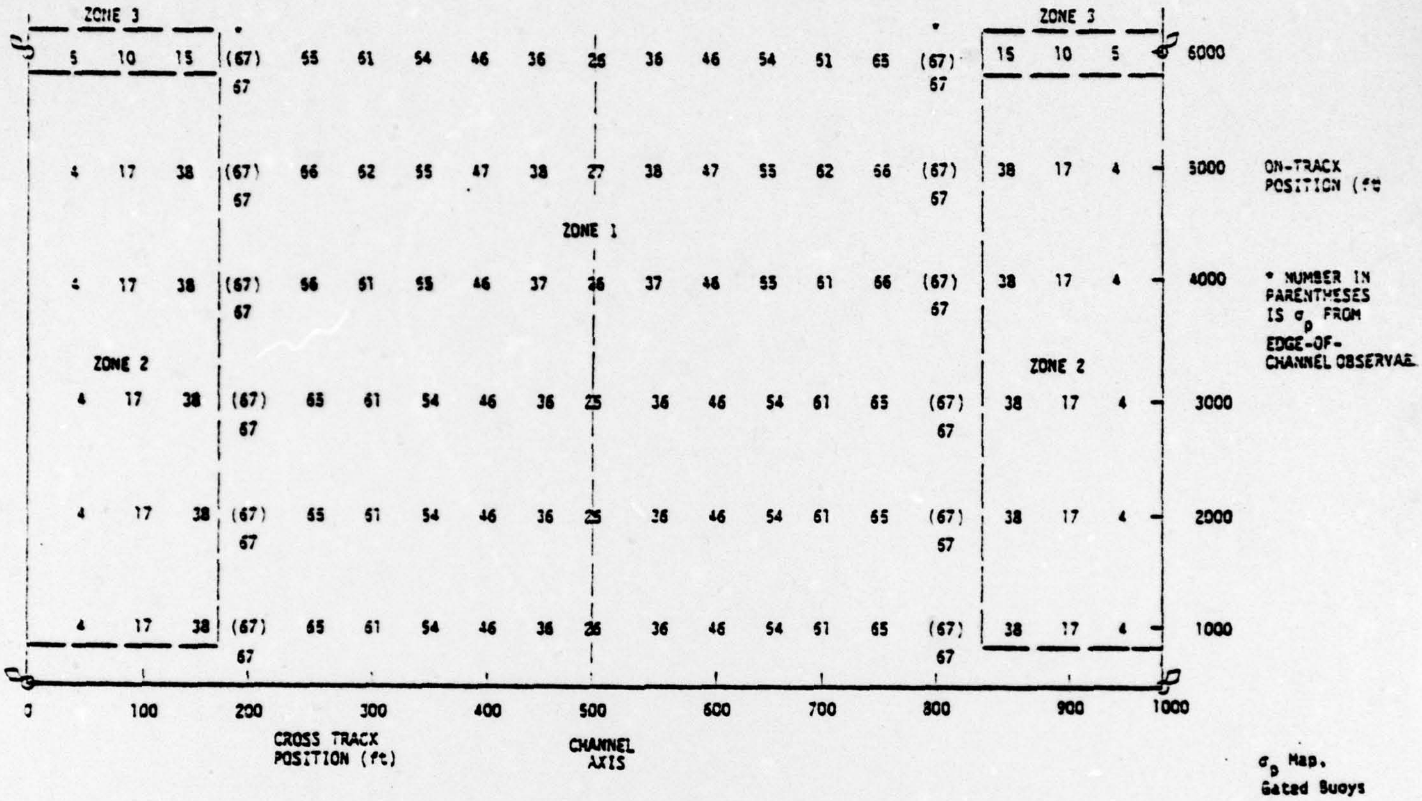

FIGURE B-20.a σ_p MAP, GATED BUOYS.

- Three zones are displayed corresponding to the observable for fixing cross-track position in the zone.
- The observable for fixing cross-track position in Zone 1 is matching visual angles.
- The observable for fixing cross-track position in Zone 2 is the apparent slope of the line of buoys marking the channel edge. Fixing cross-track position using this observable is discussed in B.I. 2.
- The observable for fixing cross-track position in Zone 3 is direct distance estimation.
- Zones 1 and 2 are arbitrarily meshed at 200 feet from each channel edge.
- Zone 3 is used only when there is a buoy abeam.

FIGURE B-20.b DISCUSSION OF σ_p MAP, GATED BUOYS.

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									ON TRACK POSITION (FT.)
10	20	30	40	50	60	70	80	90	6000
17	67	150	267	417	600	817	1067	1350	5000
17	67	150	267	417	600	817	1067	1350	4000
17	67	150	267	417	600	817	1067	1350	3000
17	67	150	267	417	600	817	1067	1350	2000
17	67	150	267	417	600	817	1067	1350	1000
10	20	30	40	50	60	70	80	90	0
100	200	300	400	500	600	700	800	900	

CROSS-TRACK POSITION (FT.)

FIGURE B-21.a σ_p MAP, BUOYS LEFT SIDE ONLY.

- Observable is apparent slope of line formed by bouys lining left side of channel.
- Error equation relating observable and P are reported in Appendix B.
- σ_p's are height-of-eye dependent. A height of eye of 60 ft. was used for this example.
- Cross-track position fixed by direct distance estimation when buoy is abeam.

FIGURE B-21.b DISCUSSION OF σ_p MAP, BUOYS LEFT SIDE ONLY.

— REAR RANGE

— FRONT RANGE

ON TRACK POSITION (N. MI.) / NAUTICAL MILES		100	200	300	400		500		600	700	800	900	
1	92	73	55	37	19	10	2	10	19	37	55	73	92
2	100	81	61	42	23	13	5	13	23	42	61	81	100
3	107	86	66	47	27	18	11	18	27	47	66	86	107
4	113	92	72	52	33	24	18	24	33	52	72	92	113
5	119	99	79	59	41	33	27	33	41	59	79	99	119
6	127	107	87	68	51	43	37	43	51	68	87	107	127

CROSS-TRACK POSITION (FT.)

FIGURE B-22.a σ_p MAP, RANGE CASE #1 (RANGE ONLY).

- Error in fixing cross-track position (σ_p) due to two components: (1) error in fixing cross-track position from a given horizontal visual angle, given the observer is a known distance from the range; and (2) error in fixing distance from the range.
- Error in horizontal visual angle is: $\sigma_\phi = 0.5' + 0.1\phi$
  where
  ϕ = visual angle
  0.5 is constant component of error.
- Error in fixing distance from range is: $\sigma_D = 0.1\,D$.
  where
  D = distance to front range.
- σ_ϕ and σ_D are propagated to cross-track position to obtain σ_p's, using standard least squares error propagation techniques.
- On range σ_p's are due only to 0.5' ambiguity.

FIGURE B-22.b DISCUSSION OF σ_p MAP, RANGE CASE #1.

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— REAR RANGE

— FRONT RANGE

(σ_p in feet)

	100	200	300	400		500		600	700	800	900		NAUTICAL MILES
52	42	32	22	12	7	2	7	12	22	32	42	52	1
60	48	37	26	14	9	3	9	14	26	37	48	60	1.5
55	45	35	25	15	10	5	10	15	25	35	45	55	2
61	51	41	31	21	16	11	16	21	31	41	51	61	3
68	58	48	38	28	23	18	23	28	38	48	58	68	4
77	67	57	47	37	32	27	32	37	47	57	67	77	5
82	72	62	52	42	37	32	37	42	52	62	72	82	5.5
87	77	67	57	47	42	37	42	47	57	67	77	87	6

ON TRACK POSITION (N. MI. FROM FRONT RANGE)

CROSS TRACK POSITION (FT.)

FIGURE B-23.a σ_p MAP, RANGE CASE #2, RANGE PLUS BUOYS ONE SIDE

- Range case #2 is same as range case #1 except that buoys are used to better estimate distance to the range.
- σ_ϕ for range case #2 is same as σ_ϕ for range case #1.
- σ_D = min. $\{0.1\ d_i;\ 0.1\ d_{i-1}\}$

  where:
  d_i = distance to nearest ahead buoy.
  d_{i-1} = distance to nearest astern buoy.

FIGURE B-23.b DISCUSSION OF σ_p MAP, RANGE CASE #2

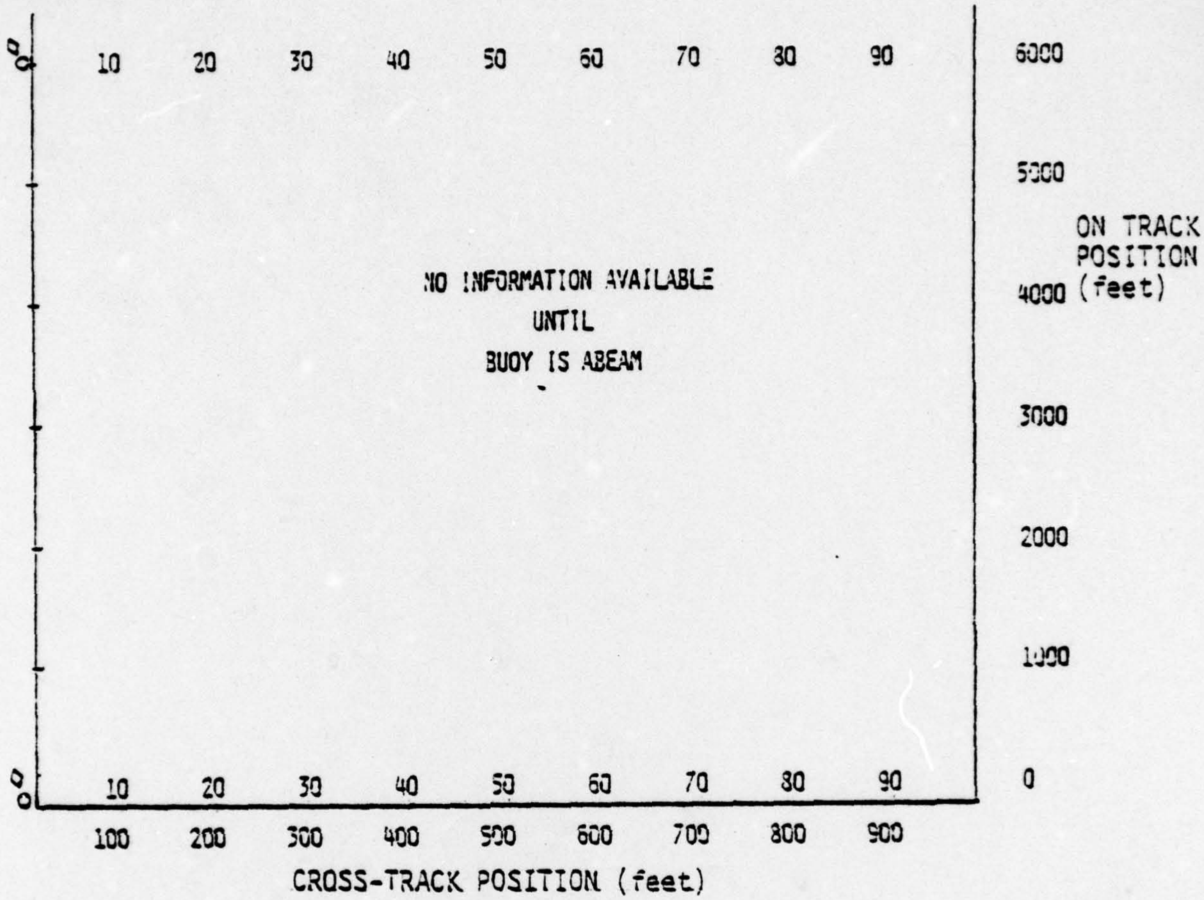

FIGURE B-24.a. σ_p Map; Buoys One Side, Poor Visibility

- Two zones are displayed. Visibility is such that buoys are visible only when the buoy is abeam. Between buoys, no buoys are visible and the mariner has no A/N information.

- The observable for fixing cross-track position is direct distance estimation to the buoy abeam.

FIGURE B-24.b Discussion for Poor Visibility Case.

95/c

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ON TRACK POSITION (FT)	100	200	300	400	500	600	700	800	900	1000
6000	15	16	18	18	17	17	17	17	18	18
5000	10	20	30	40	50	60	70	80	90	100
4000	10	20	30	40	50	60	70	80	90	100
3000	10	20	30	40	50	60	70	80	90	100
2000	10	20	30	40	50	60	70	80	90	100
1000	10	20	30	40	50	60	70	80	90	100
	15	16	18	18	17	17	17	17	18	18

CROSS-TRACK POSITION (FT.)

FIGURE B-25.a σ_p MAP: RADAR, BUOYS LEFT SIDE ONLY.

- Contributor to error in region between buoys is ability to align cursor on PPI scope and estimate distance to side of channel marked by buoys.
- Timing errors and bearing errors do not substantially contribute in this region, since the effects of timing errors is to lengthen or foreshorten the apparent channel displayed on the screen, and the effect of bearing error is to rotate the apparent channel marked by the buoys and displayed on the screen.
- Errors in the region where there is a buoy abeam are due to errors affecting directed estimate of distance to the buoy:
  - timing errors;
  - resolution of range read-out,
  - correction of slant range to horizontal range.

FIGURE B-25.b DISCUSSION OF σ_p MAP; RADAR, BUOYS LEFT SIDE ONLY.

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ON TRACK POSITION (feet)	100	200	300	400	500	600	700	800	900
6000	74	74	74	74	74	74	74	74	74
5000	74	74	74	74	74	74	74	74	74
4000	74	74	74	74	74	74	74	74	74
3000	74	74	74	74	74	74	74	74	74
2000	74	74	74	74	74	74	74	74	74
1000	74	74	74	74	74	74	74	74	74
0	74	74	74	74	74	74	74	74	74

CROSS-TRACK POSITION (feet)

FIGURE B-26.a σ_p MAP: LORAN-C

- It was assumed that the mariners would not transit the waterway using Loran information alone unless he had knowledge that the "fixed" errors (due to survey, approximation in calculation propagation velocities, etc.) has been compensated for.
- The mean square radial error was determined by calculating the error gradient, using the coordinates of the actual LORAN stations, and the time difference error as the RMS value of the time differences due to nominal values for transmitting system instabilities, receiver instabilities and errors, and atmosphere noise.
- Only one component of the error (cross-track) was of interest. This was approximated as the mean square radial error divided by $\sqrt{2}$.
- The result was an error gradient of 1.08 feet per nano-second and an RMS time difference error of 97 nsec. The RMS error for the cross-track component was taken as $(97 \times 1.08) / \sqrt{2} = 74'$.
- The phase II model will compute the N-S and E-W error components separately to define the error elipse. The cross-track component can then be extracted for any given channel course line.

FIGURE B-26.b. DISCUSSION OF σ_p MAP: LORAN C CASE

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Vessel Maneuvering Simulation, Final Report, Haruzo Eda, for the Department of Transportation, United States Coast Guard, Office of Research and Development, Wash. D. C. July 1976.

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